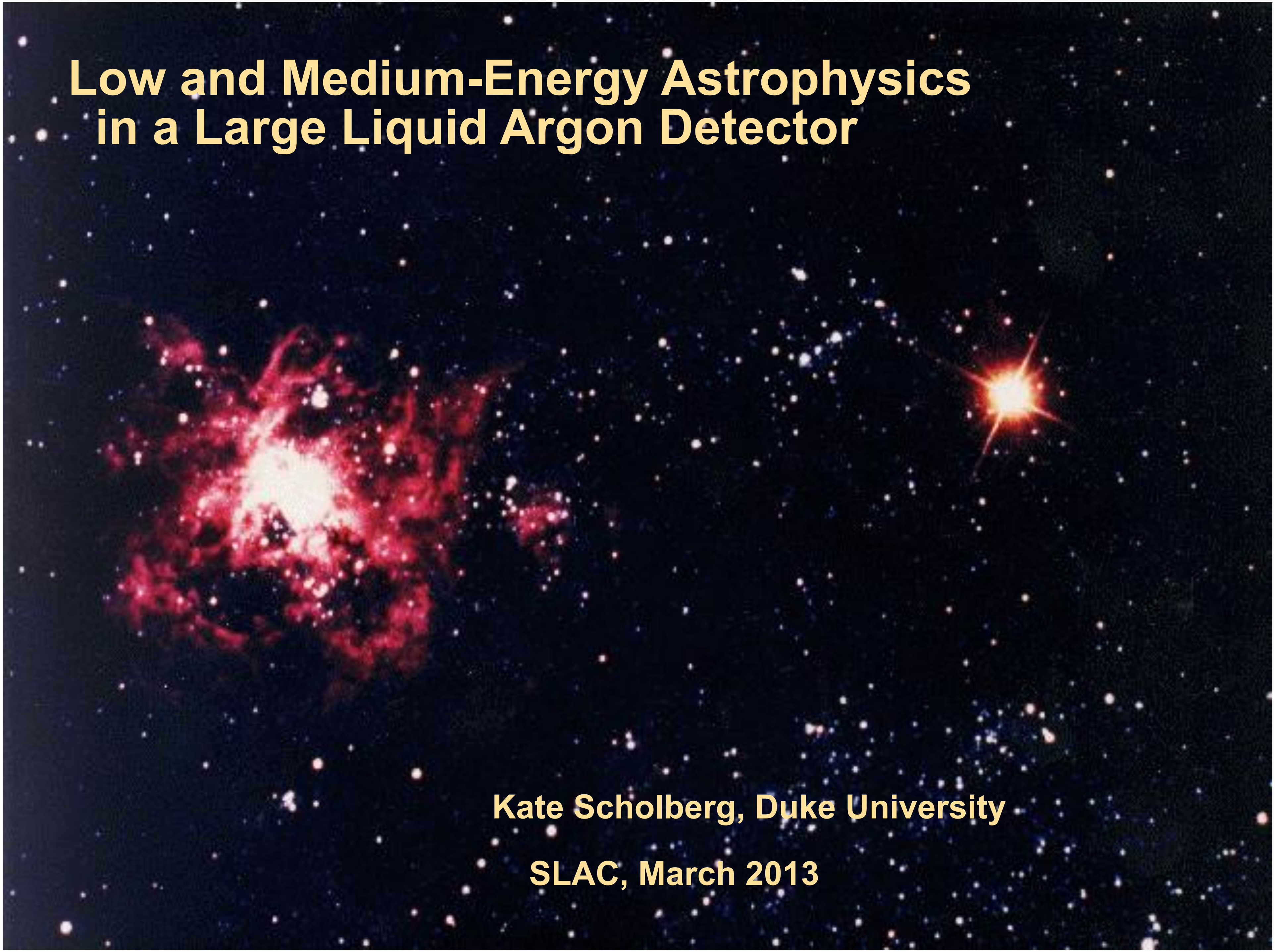
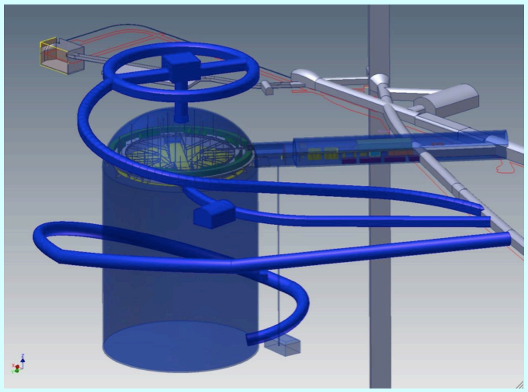
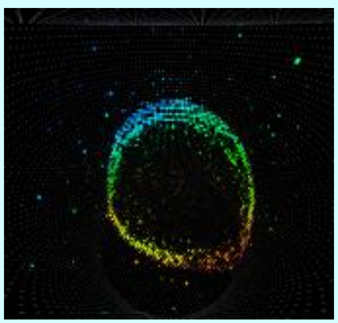
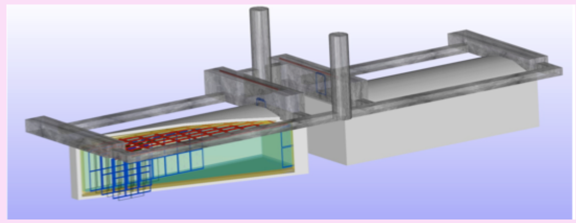
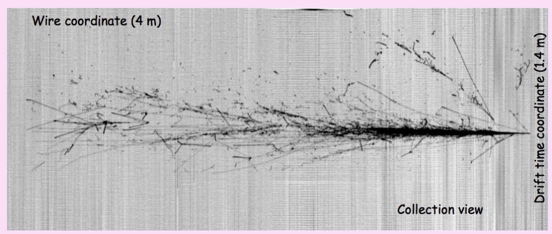
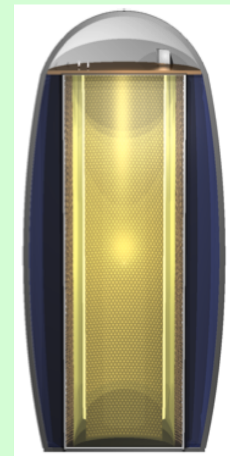
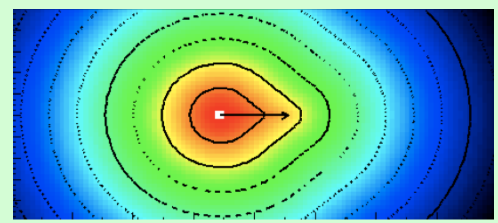
Low and Medium-Energy Astrophysics in a Large Liquid Argon Detector



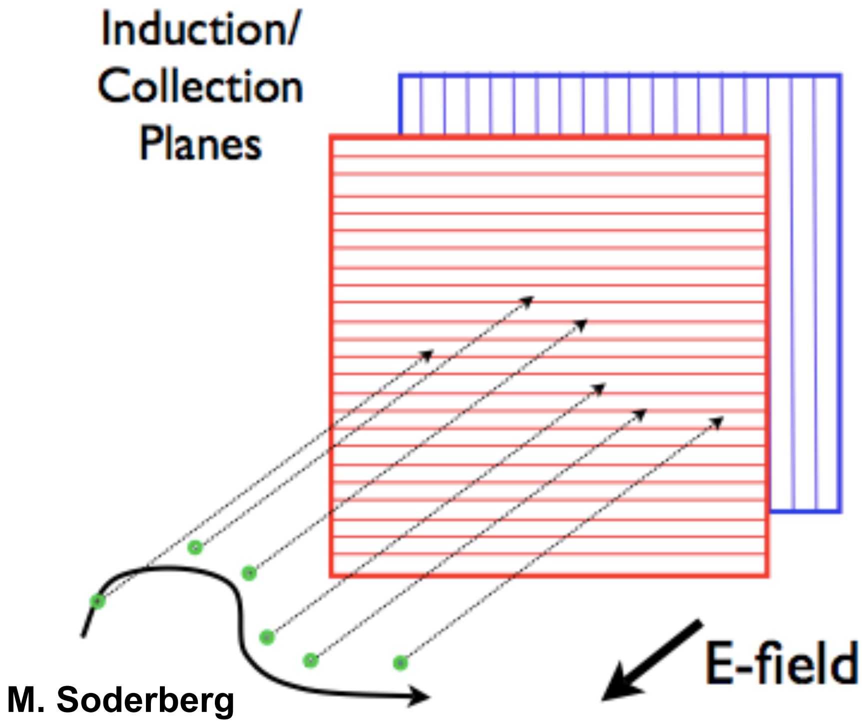
Kate Scholberg, Duke University

SLAC, March 2013

Possible large (multi-kton) detector technologies

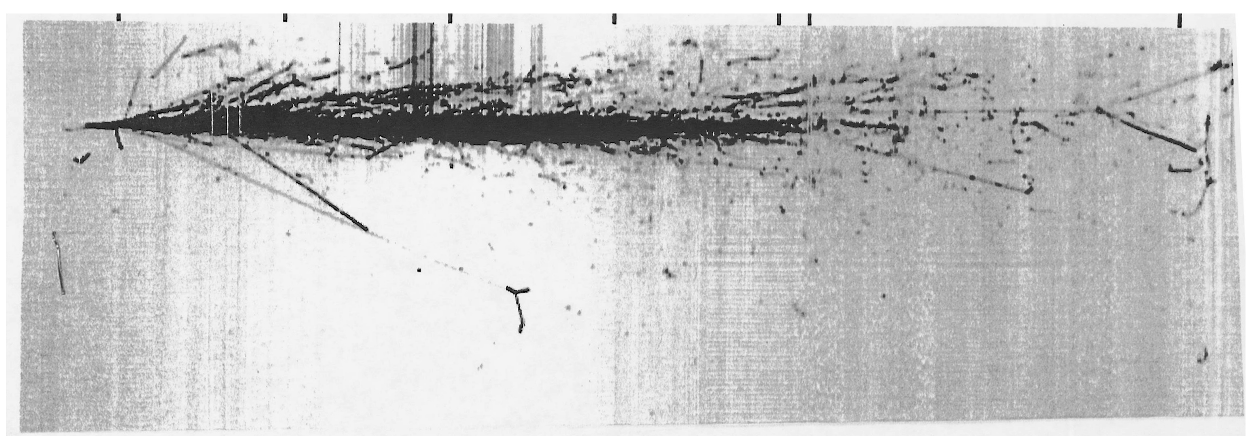
Water Cherenkov	Liquid Argon	Liquid Scintillator
 	 	 
Cheap material, proven at very large scale	Excellent particle reconstruction	Low energy threshold

Liquid argon time projection chambers

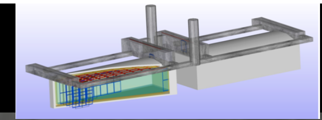


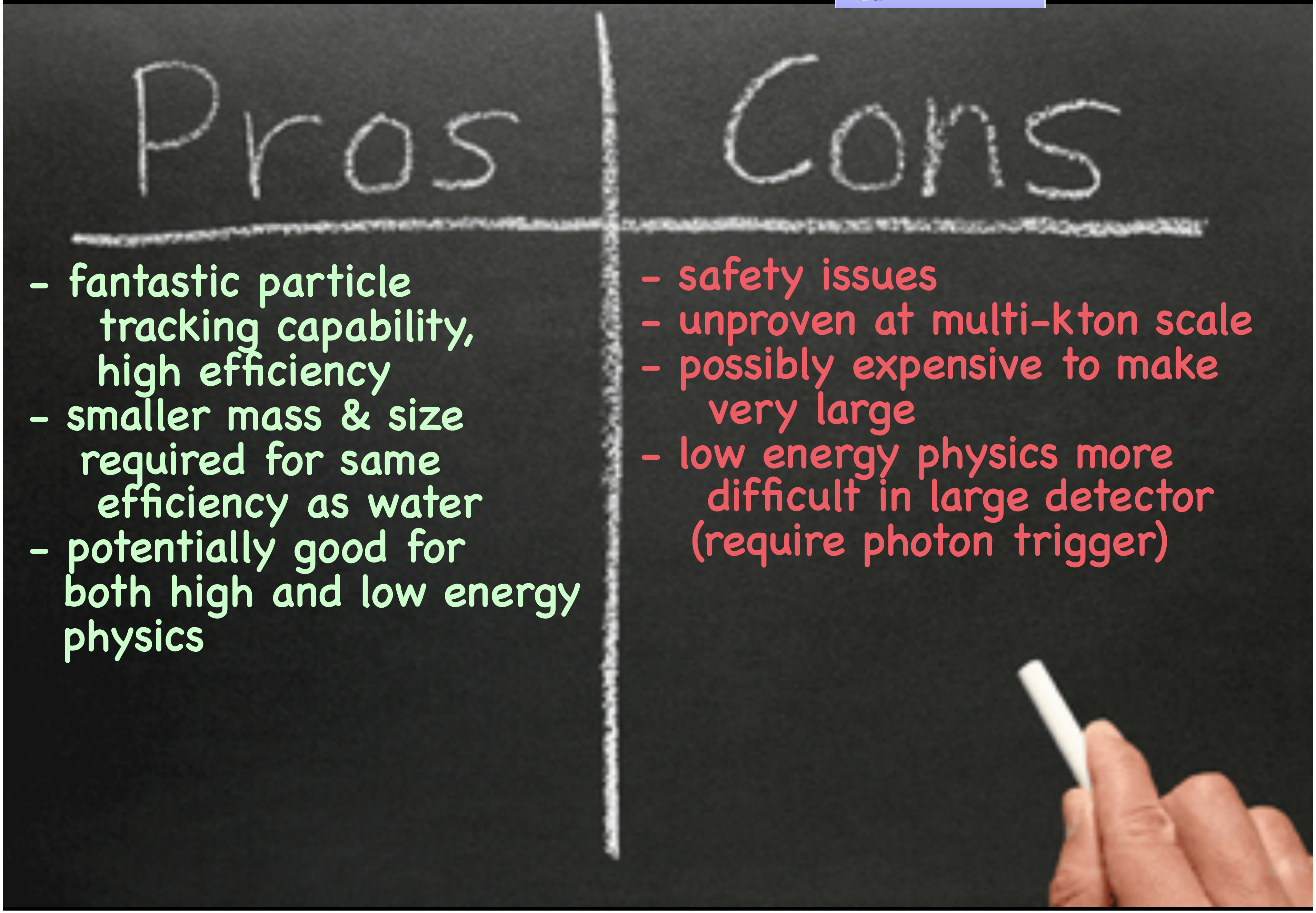
Ionization charge drifted and collected; 3D track using time info

- very high quality particle reconstruction possible
- need scintillation light (photosensors) for absolute time
- require very high purity, cryogenic liquid



Liquid Argon





Pros

- fantastic particle tracking capability, high efficiency
- smaller mass & size required for same efficiency as water
- potentially good for both high and low energy physics

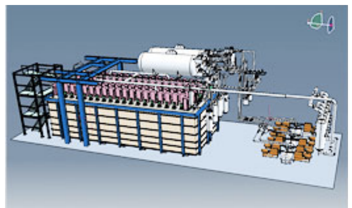
Cons

- safety issues
- unproven at multi-kton scale
- possibly expensive to make very large
- low energy physics more difficult in large detector (require photon trigger)

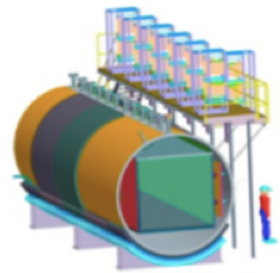
Large liquid argon detector instances

2000 **2010** **2020**

Icarus

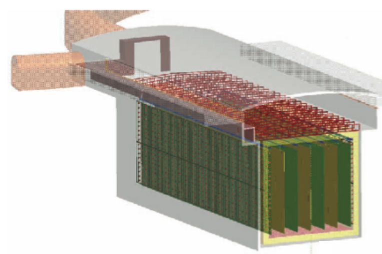


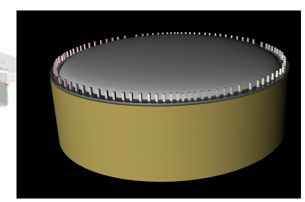
@CERN?

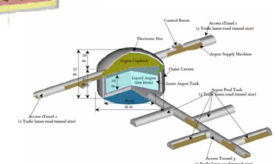


MicroBooNE

Next generation





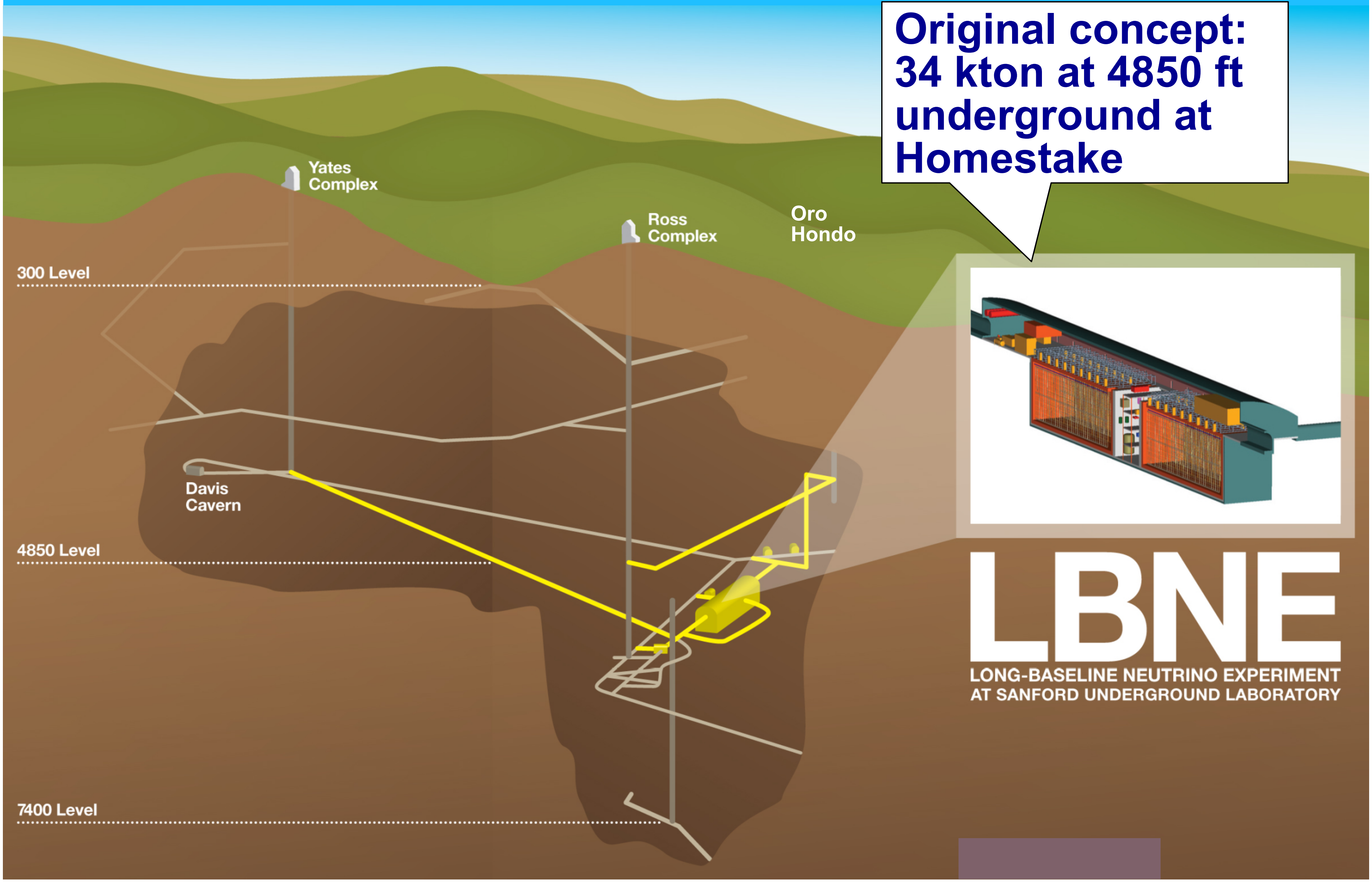


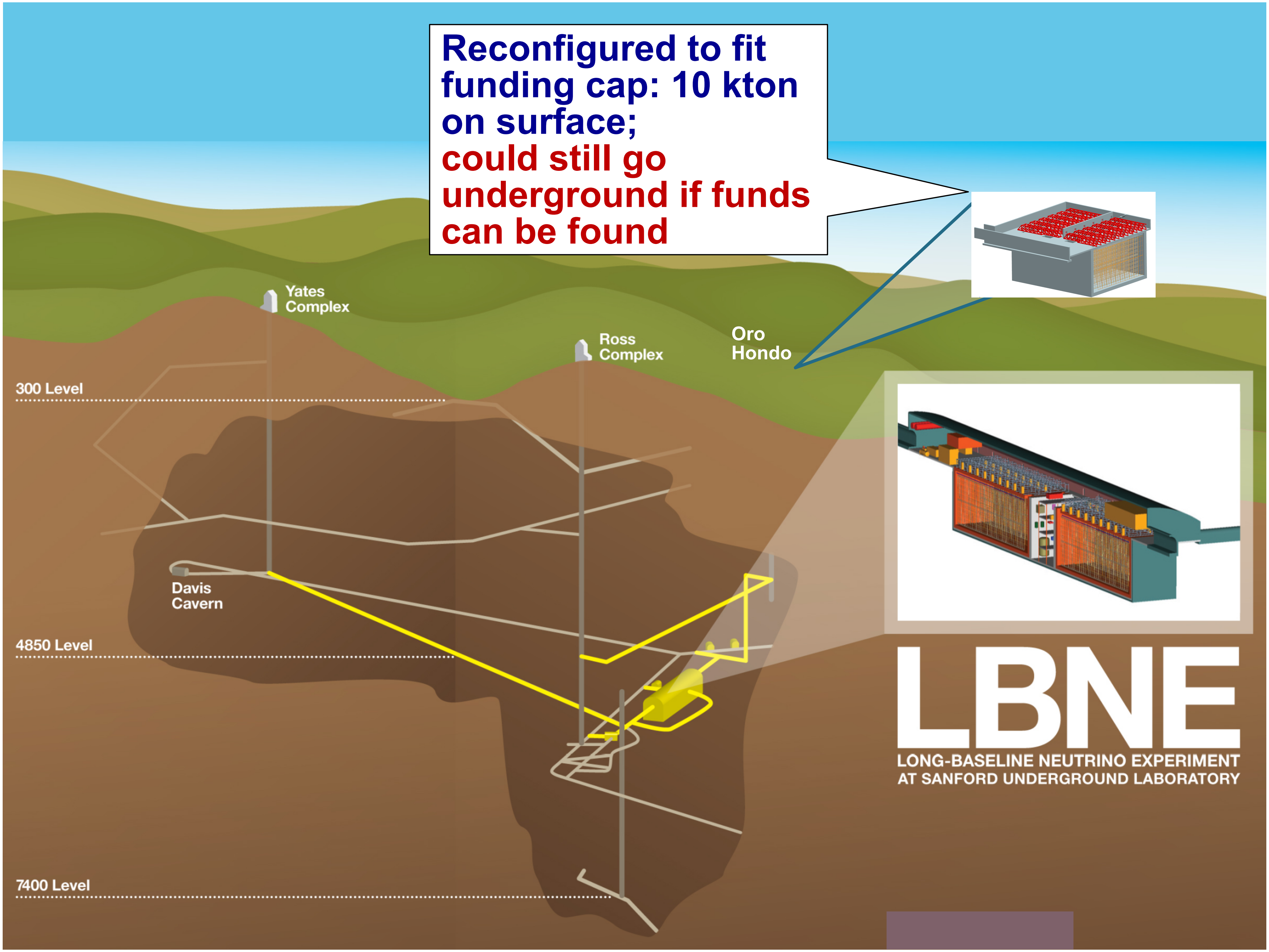
??

+ many `R&D' instances

The Long-Baseline Neutrino Experiment

next-generation large LAr TPC

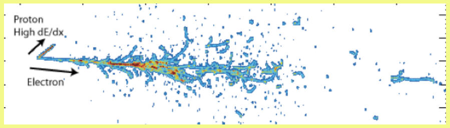


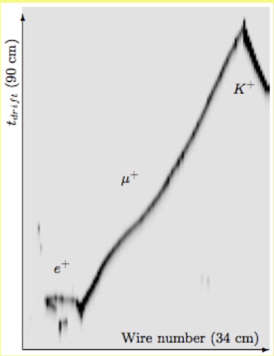

Reconfigured to fit funding cap: 10 kton on surface;
could still go underground if funds can be found
Yates Complex
Ross Complex
Oro Hondo
300 Level
Davis Cavern
4850 Level
7400 Level
LBNE
LONG-BASELINE NEUTRINO EXPERIMENT
AT SANFORD UNDERGROUND LABORATORY

LBNE physics signals

Signal	Energy range	Expected Signal Rate per kton of LAr (s^{-1} $kton^{-1}$)
Beam neutrinos (CP violation/ mass hierarchy)	~ GeV	5×10^{-4} osc ν_e in beam window
Proton decay	~ GeV	$< 2 \times 10^{-9}$
Atmospheric neutrinos	0.1-10 GeV	$\sim 10^{-5}$
Supernova burst neutrinos	few-50 MeV	~3 @ 10 kpc over ~30 secs
Solar neutrinos	few-15 MeV	4×10^{-5}
Supernova relic neutrinos	20-50 MeV	$< 2 \times 10^{-9}$

low and medium energy astro physics





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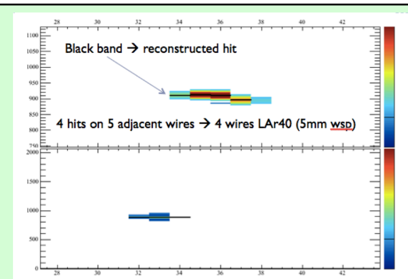
handsome, distinctive events

crummy little stubs



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Easy to pick from bg due to beam time & direction

Easy to pick from bg, but highly intolerant of bg

Easy to pick, somewhat more tolerant of bg

Potentially harder to select (esp. low energy end) *but arrive in a burst* (and bg can be well known)

Very hard to select *and* intolerant of bg

Hard to select *and* intolerant of bg

Neutrinos from core collapse

When a star's core collapses, ~99% of the gravitational binding energy of the proto-nstar goes into ν's of *all flavors* with ~tens-of-MeV energies

(Energy *can* escape via ν's)

Mostly ν-$\bar{\nu}$ pairs from proto-nstar cooling

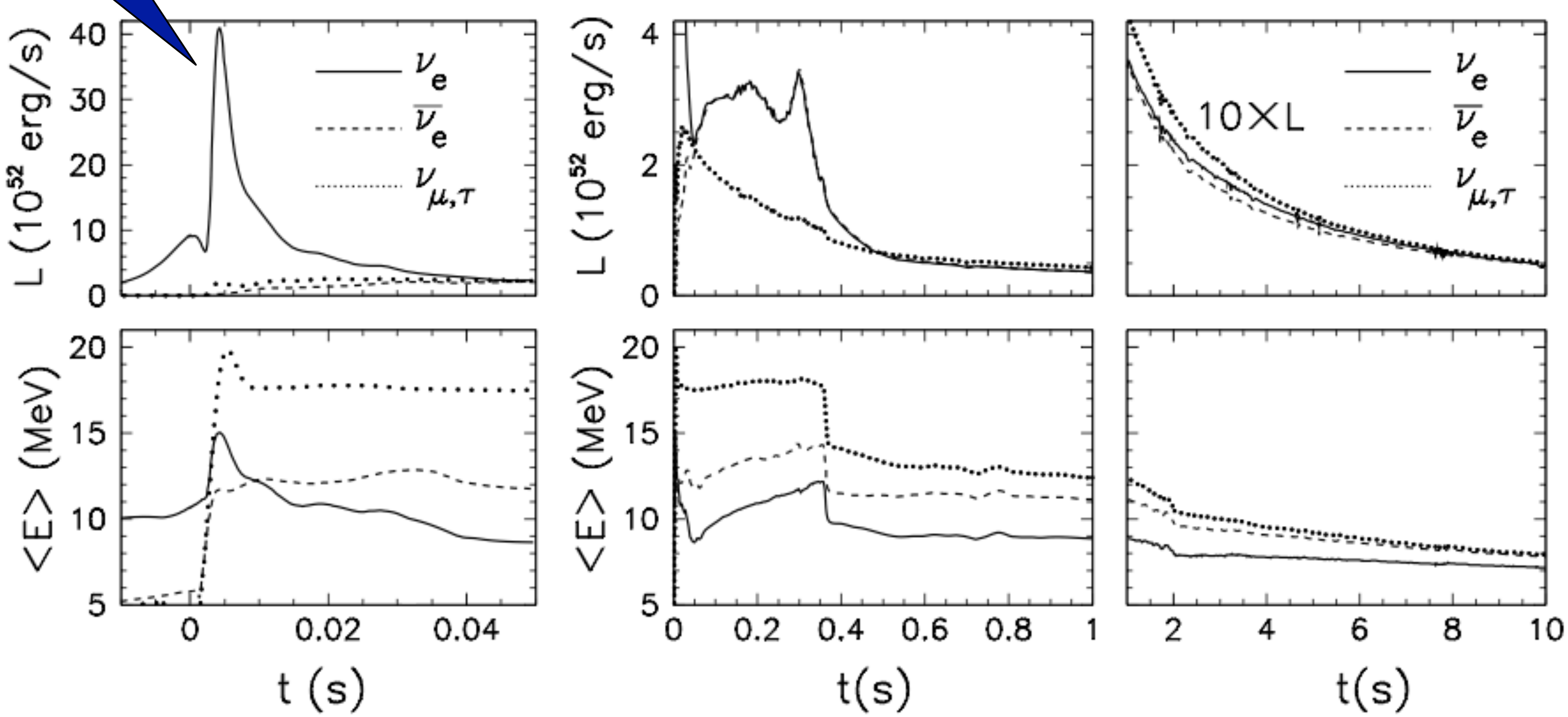
Timescale: *prompt* after core collapse, overall Δt~10's of seconds

Expected neutrino luminosity and average energy vs time

Fischer et al., arXiv:0908.1871: 'Basel' model

neutronization burst

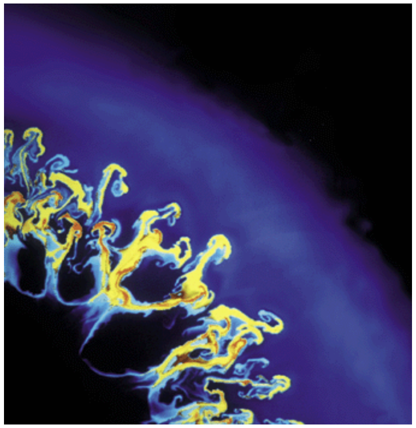
Early: deleptonization | **Mid: accretion** | **Late: cooling**



Generic feature:
(may or may not be robust)

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

What We Can Learn

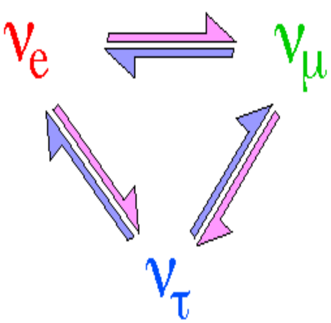


CORE COLLAPSE PHYSICS

- explosion mechanism
- proto nstar cooling, quark matter
- black hole formation
- accretion disks
- nucleosynthesis

from flavor, energy, time structure of burst

NEUTRINO/OTHER PARTICLE PHYSICS

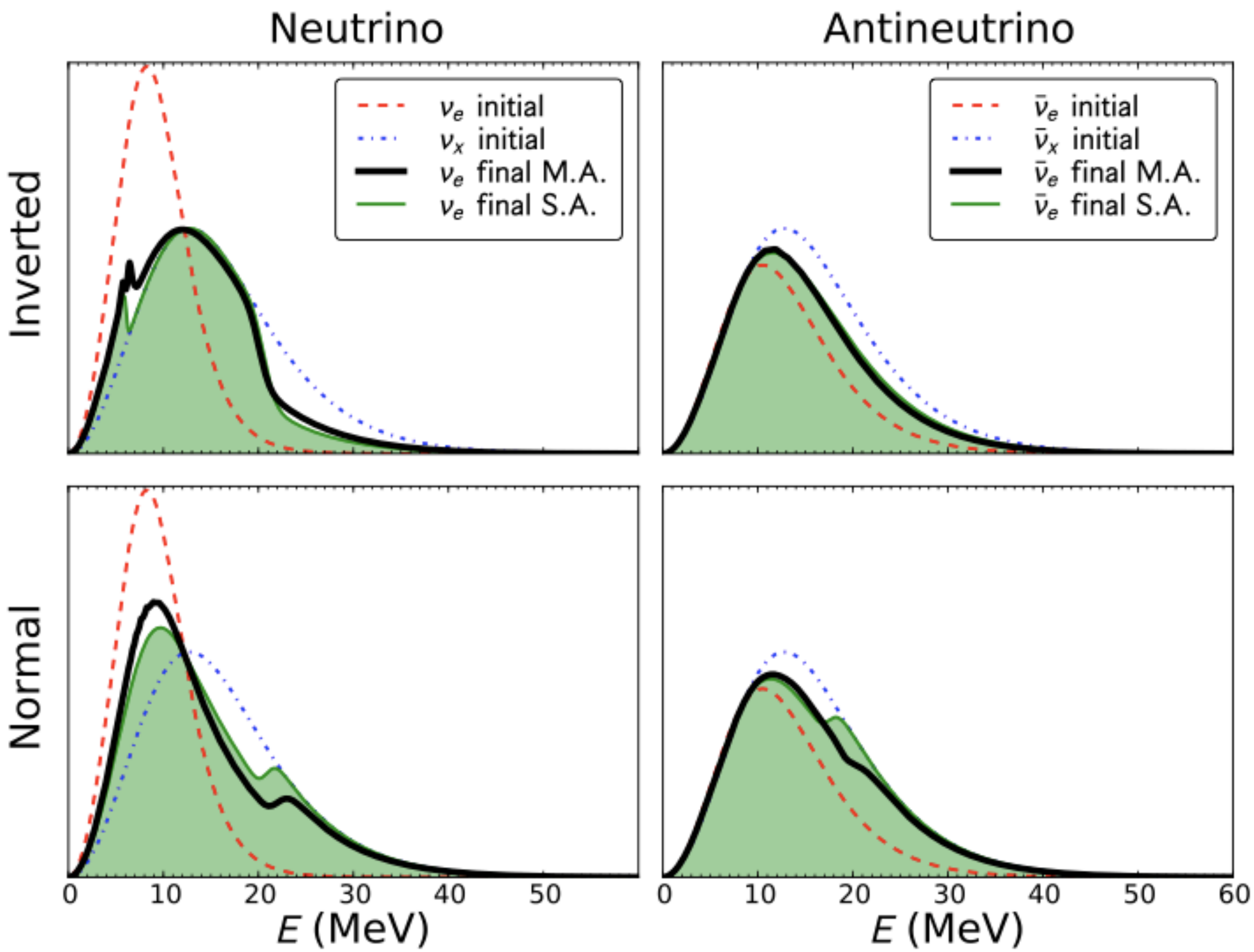


- ν absolute mass (not competitive)
- ν mixing from spectra: flavor conversion in SN/Earth
- other ν properties: sterile ν's, magnetic moment,...
- axions, extra dimensions, FCNC, ...

+ EARLY ALERT

Example: collective effects

Duan & Friedland, arXiv:1006.2359



***Distinctive spectral swap features depend on neutrino mass hierarchy*, for neutrinos vs antineutrinos**

Experimentally, can we tell the difference?

Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; ignoring for now

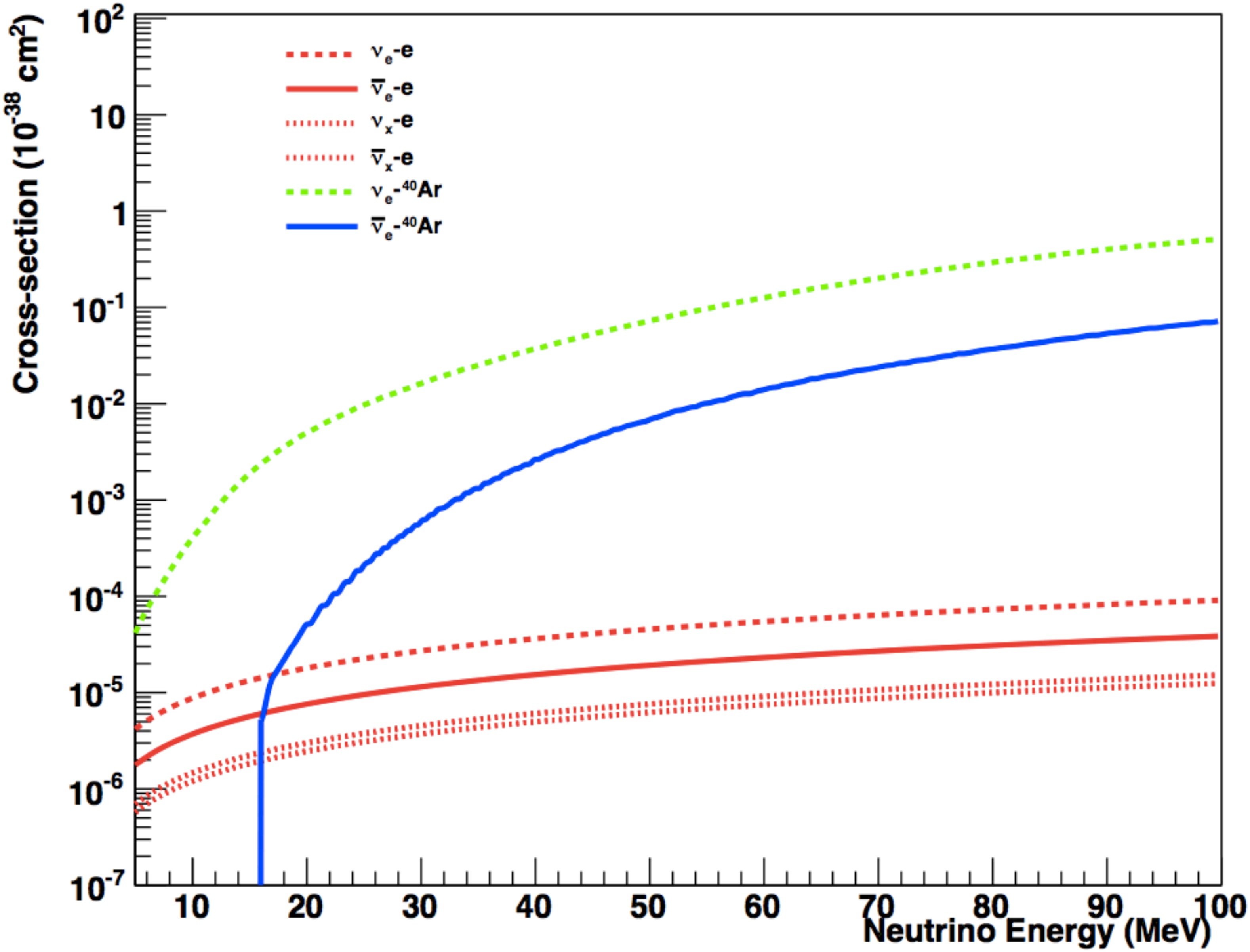
Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...

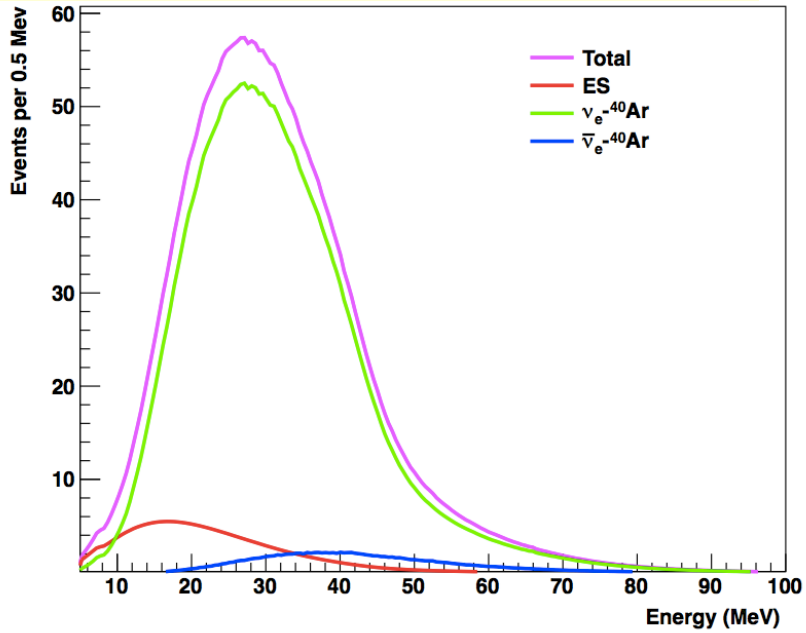
Cross-sections for interactions in argon



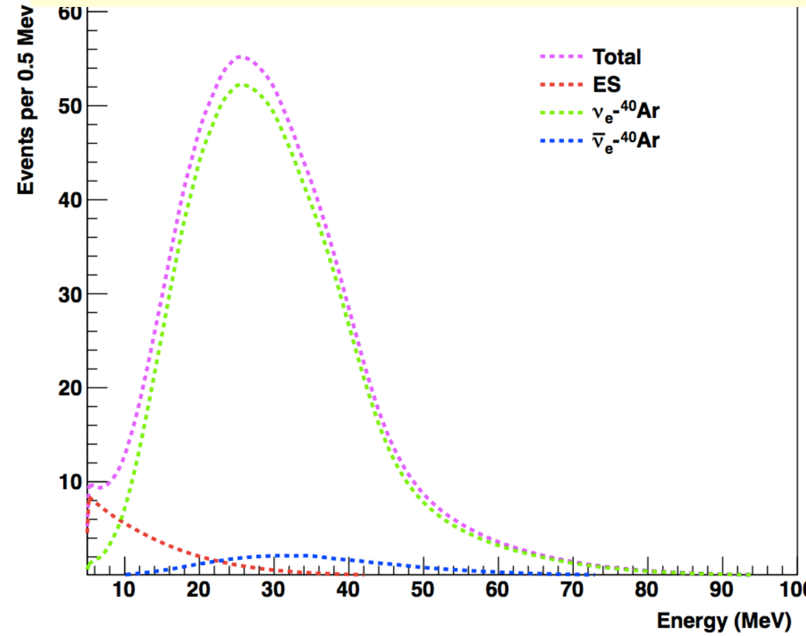
Supernova signal in LAr

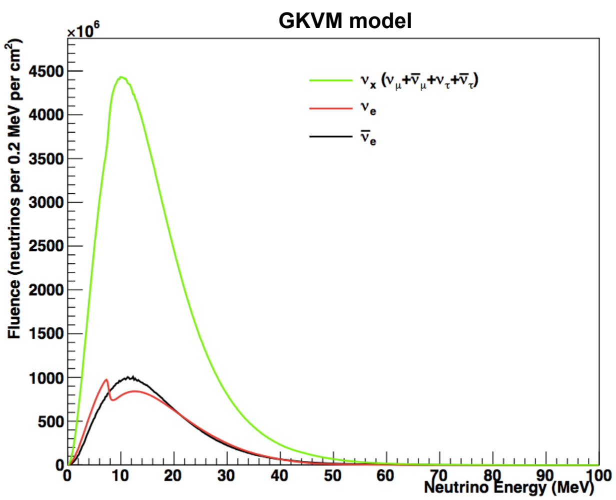
SN @ 10 kpc, 34 kton

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy





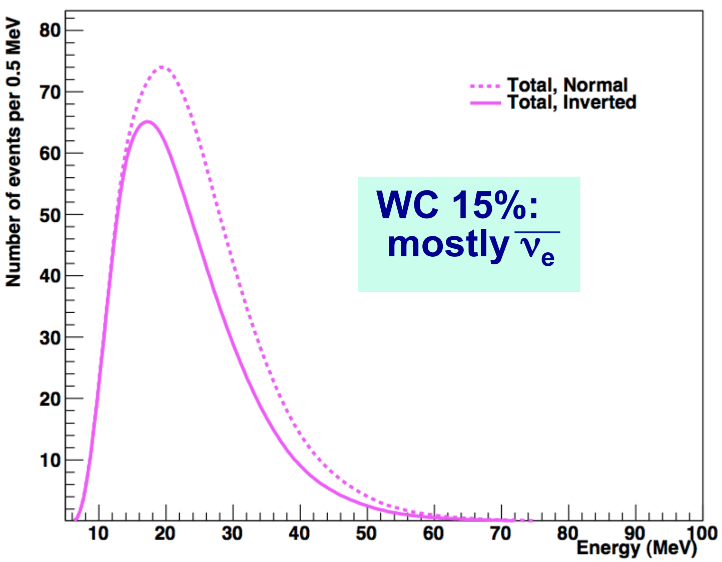
Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	3160	2798

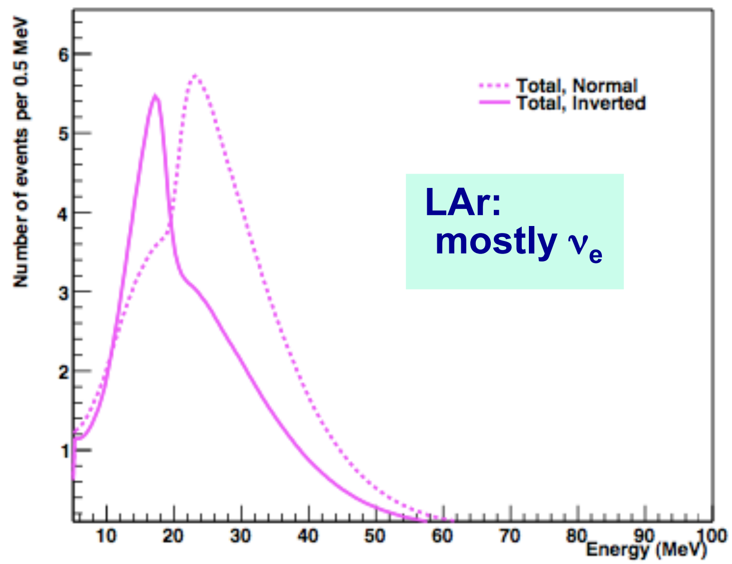
Dominated by ν_e

Observability of oscillation features: example

Can we tell the difference between normal and inverted mass hierarchies?

(1 second late time slice, flux from H. Duan w/collective effects)





Differences, but no sharp features

LAr shows dramatic difference

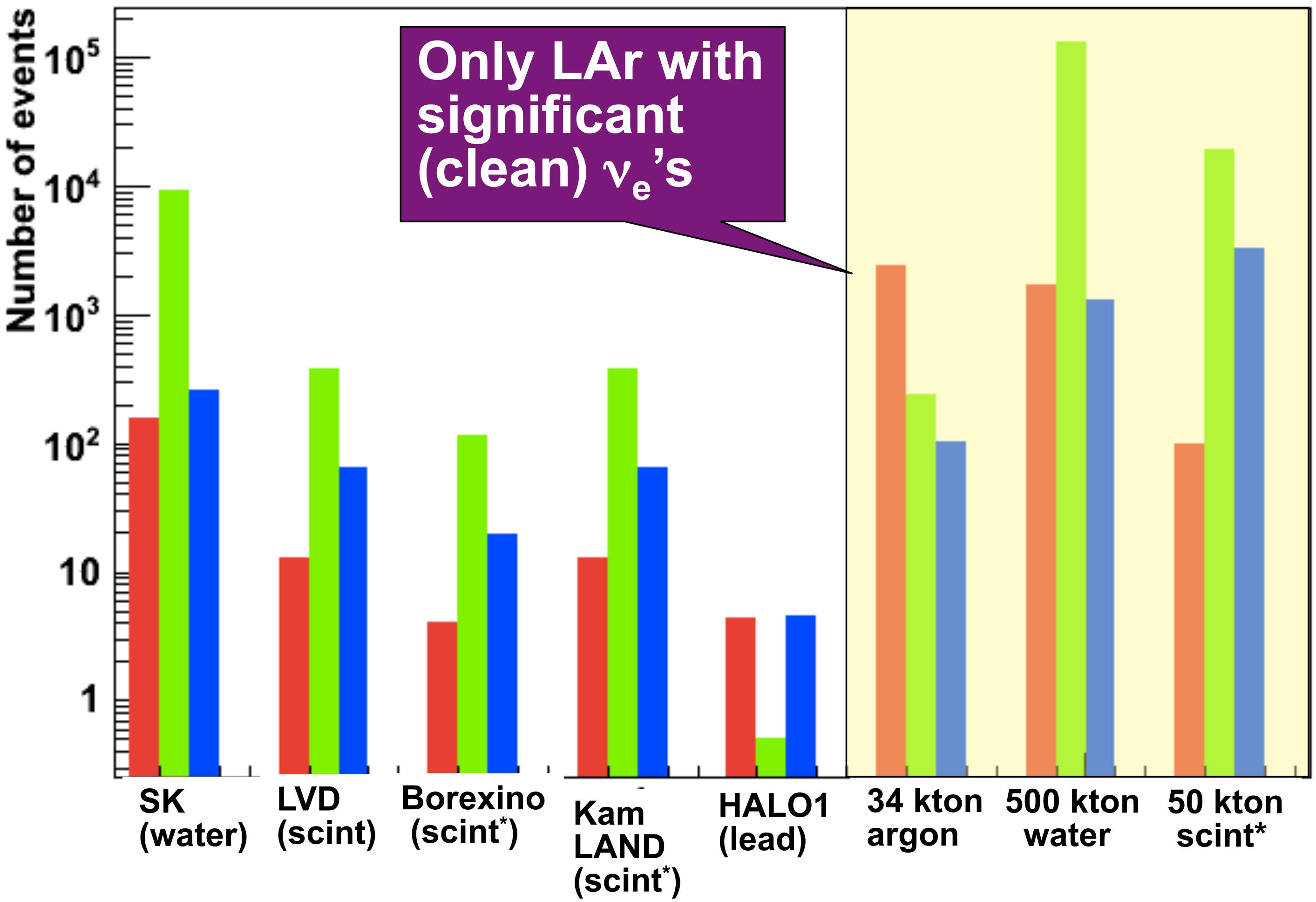
\`Anecdotal' evidence is good... systematic surveys underway

World SN flavor sensitivity

for largest detectors of each class

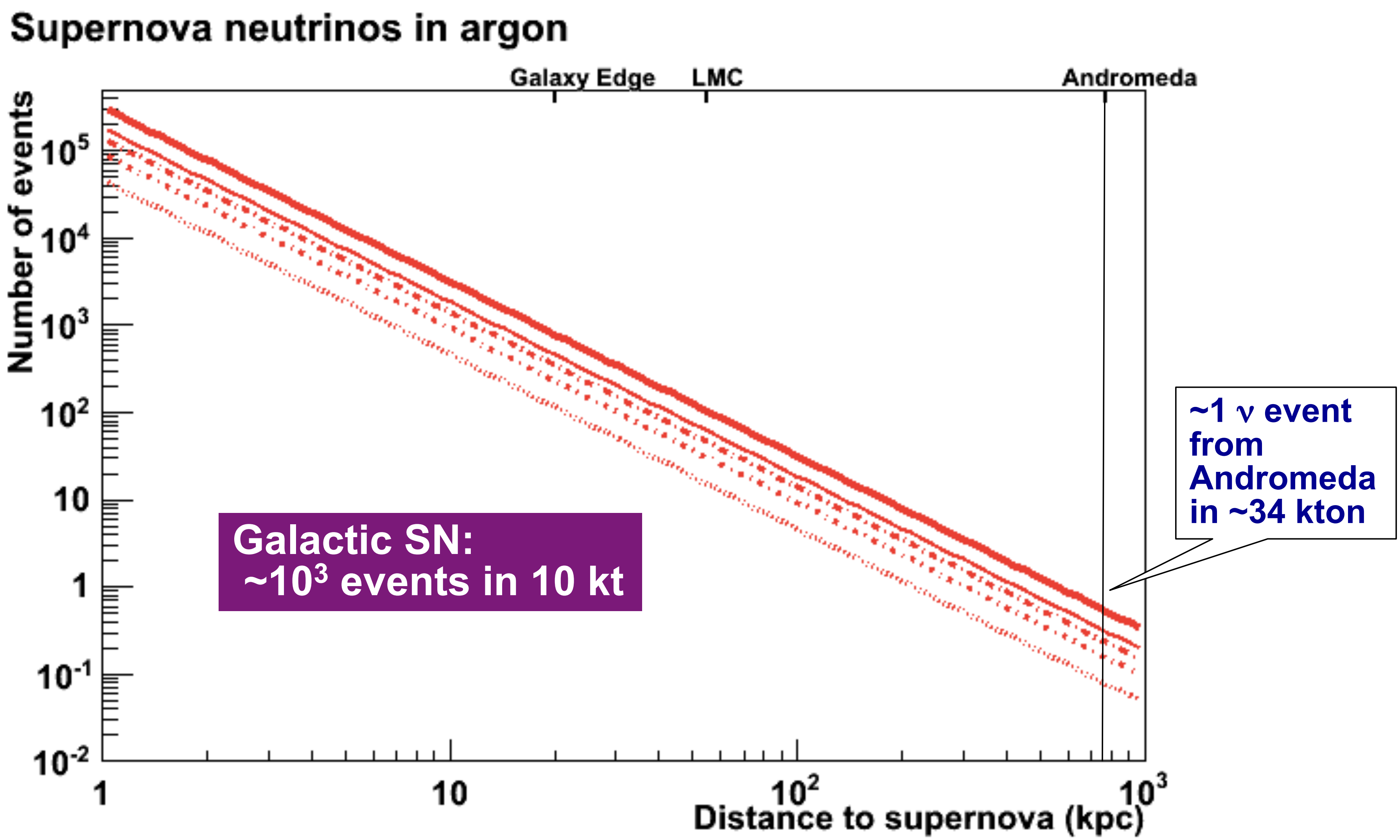
Electron neutrino
Electron antineutrino
Muon and tau neutrino and antineutrino

Livermore model
@ 10 kpc



* plus NC ν-p scattering

Signal rates vs distance for LBNE configurations



5, 10, 15, 20, 34 kton

Work underway for LBNE

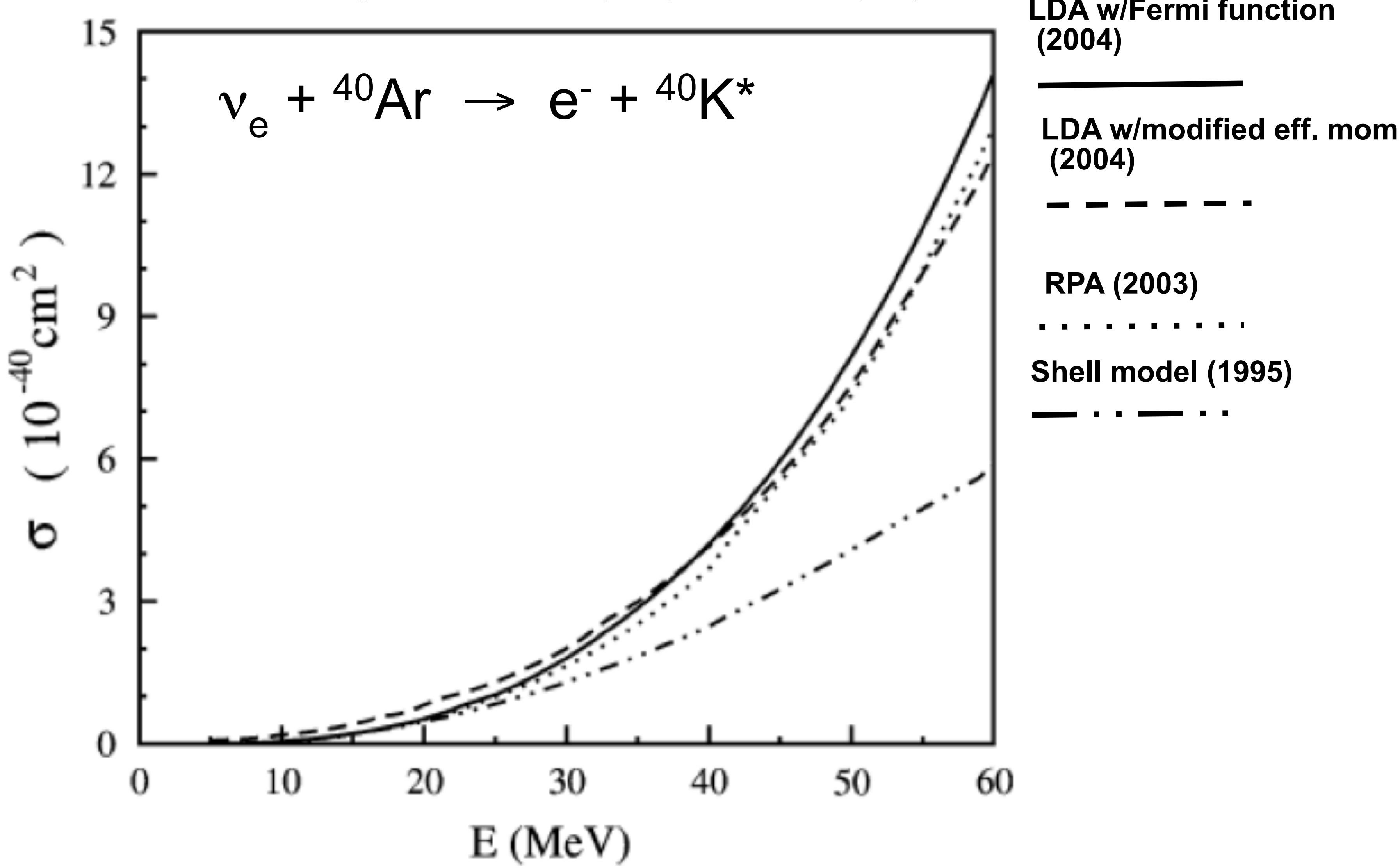
- Cross sections for ν-Ar interactions at low energy
- Realistic LAr TPC detector response:

  Efficiency, resolution, tagging
- Backgrounds:

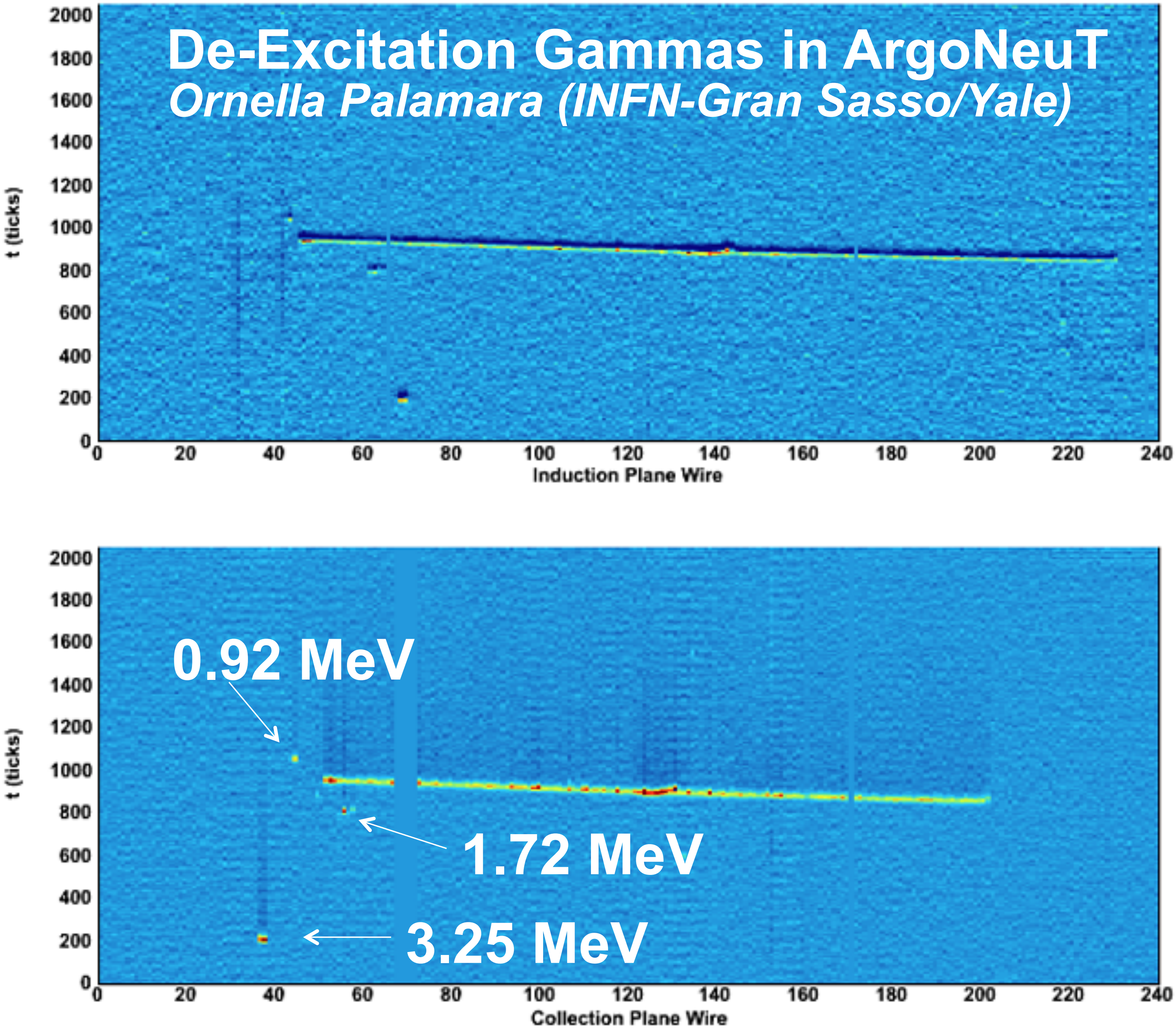
  especially cosmogenics

Cross sections for CC electron neutrino absorption

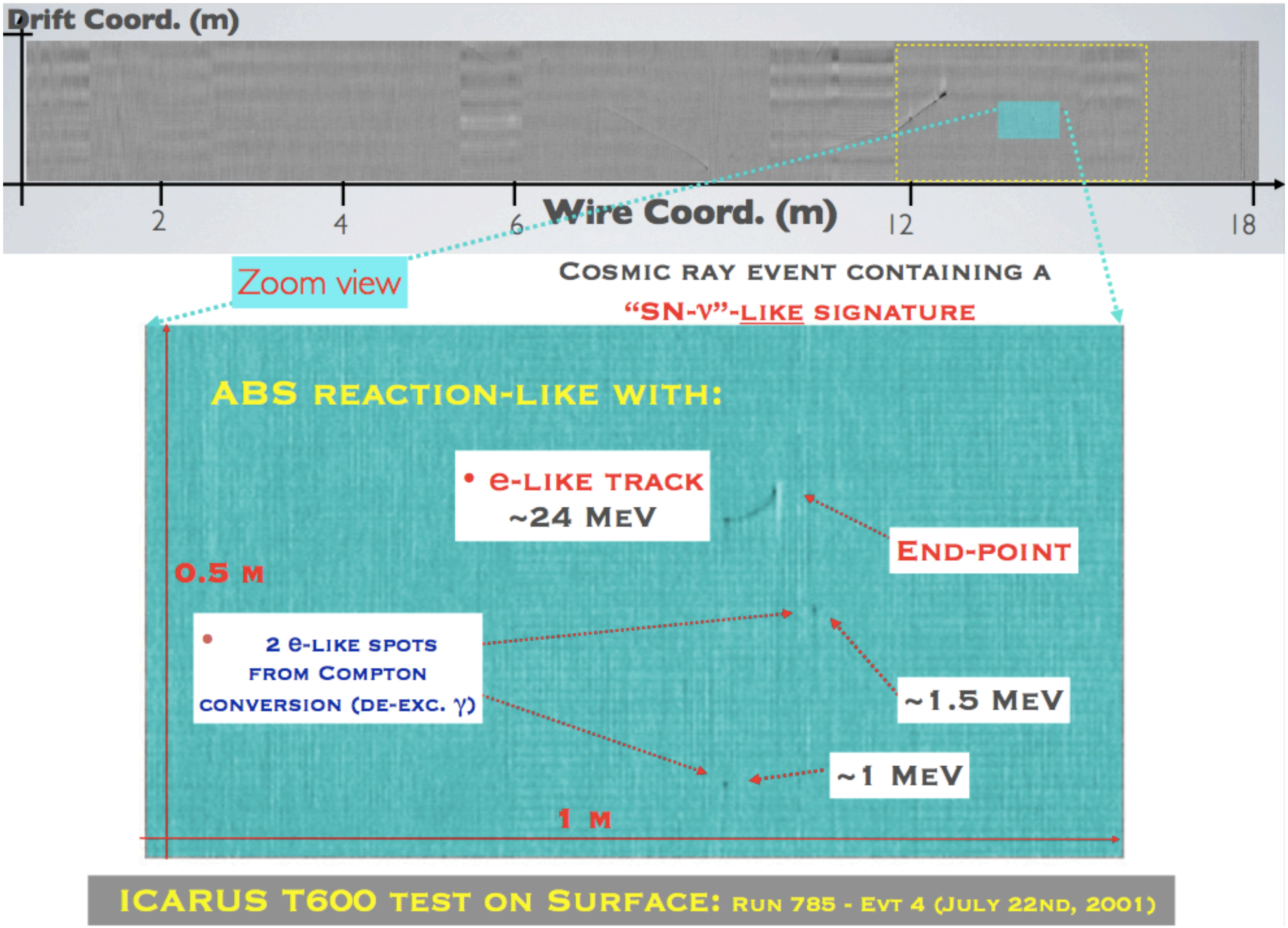
M. Sajjad Athar and S.K. Singh, Phys. Lett. B591, 69 (2004)



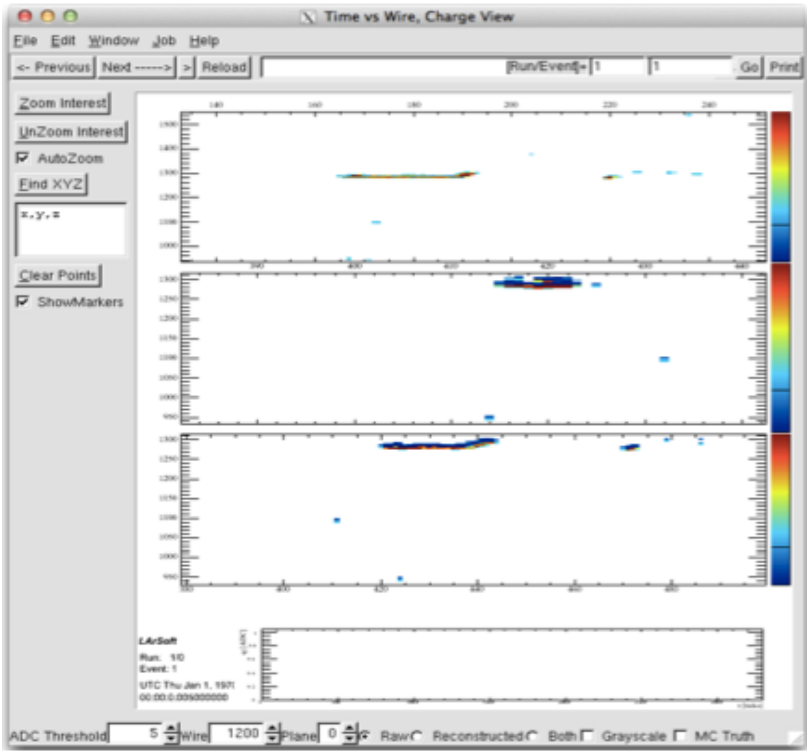
Need to measure deexcitation γ's!


De-Excitation Gammas in ArgoNeuT
Ornella Palamara (INFN-Gran Sasso/Yale)
t (ticks)
Induction Plane Wire
t (ticks)
Collection Plane Wire
0.92 MeV
1.72 MeV
3.25 MeV

From Flavio Cavanna (SNS workshop, May 2012)



LArTPC Detector Response



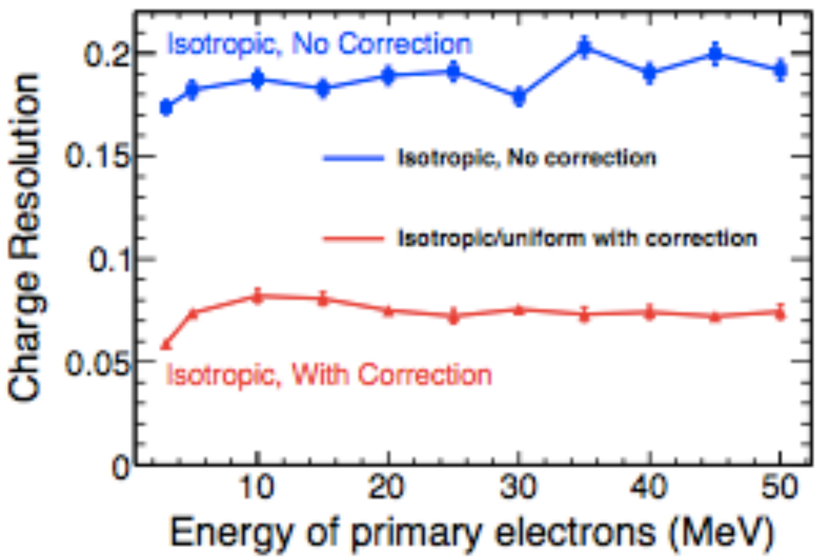
Example event display for 30 MeV electron
(μBooNE geometry)

- energy resolution?
- vertex resolution?
- directional resolution?
- detection & reconstruction efficiency?

much of this can be addressed at some level with simulation... but simulation needs to be *validated* with data

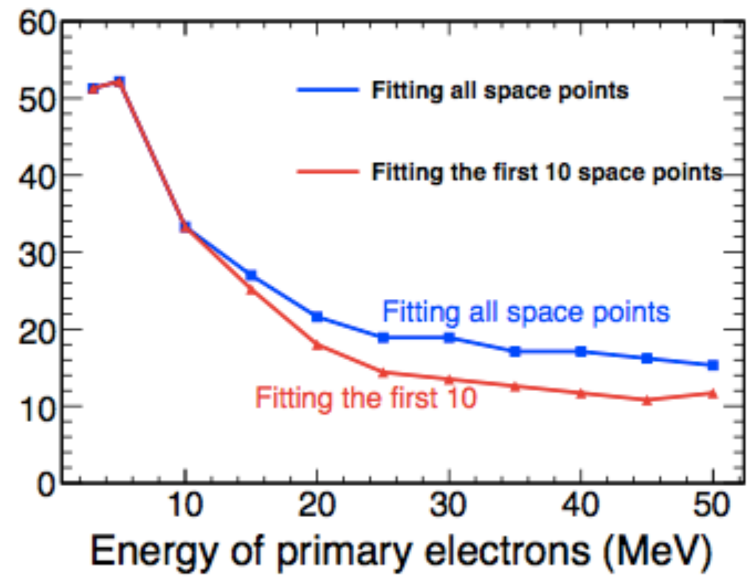
LArSoft Low-Energy Event studies (Z. Li)

Preliminary studies w/MicroBooNE geometry: looks somewhat worse than Icarus paper



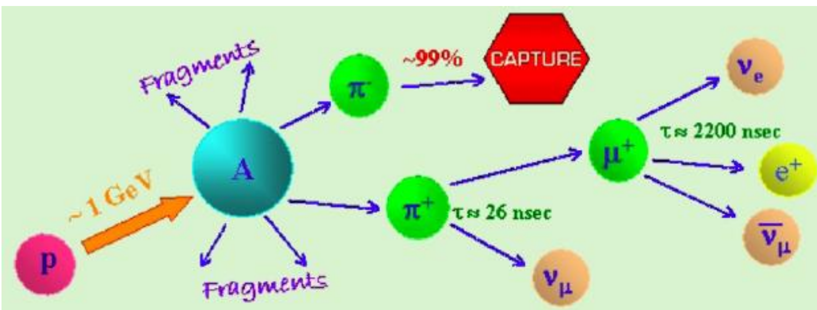
using charge in the collection plane; drift correction using MC truth

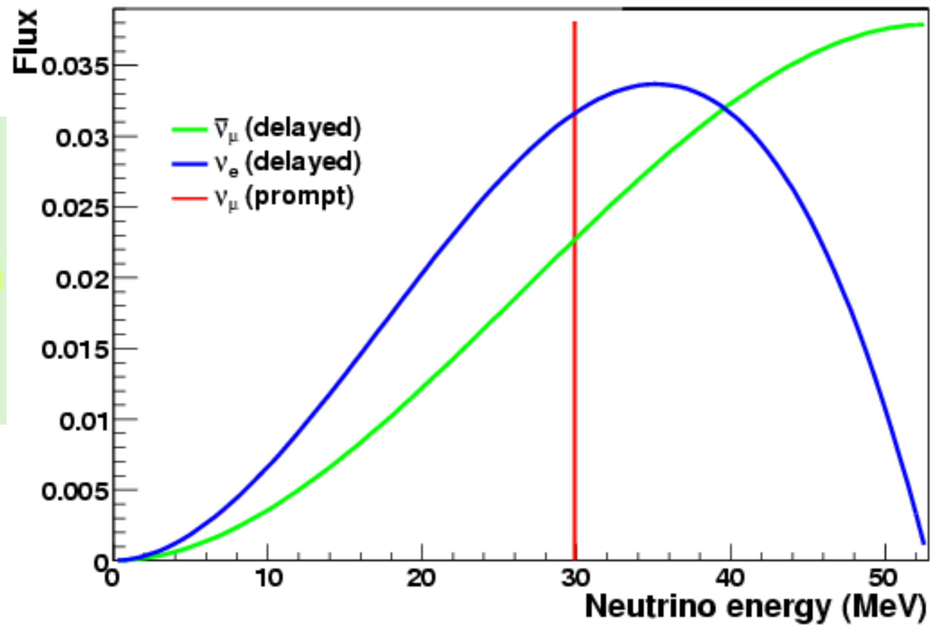
Direction resolution (degrees)



Preliminary

Measure these low-energy interactions with stopped-pion neutrinos





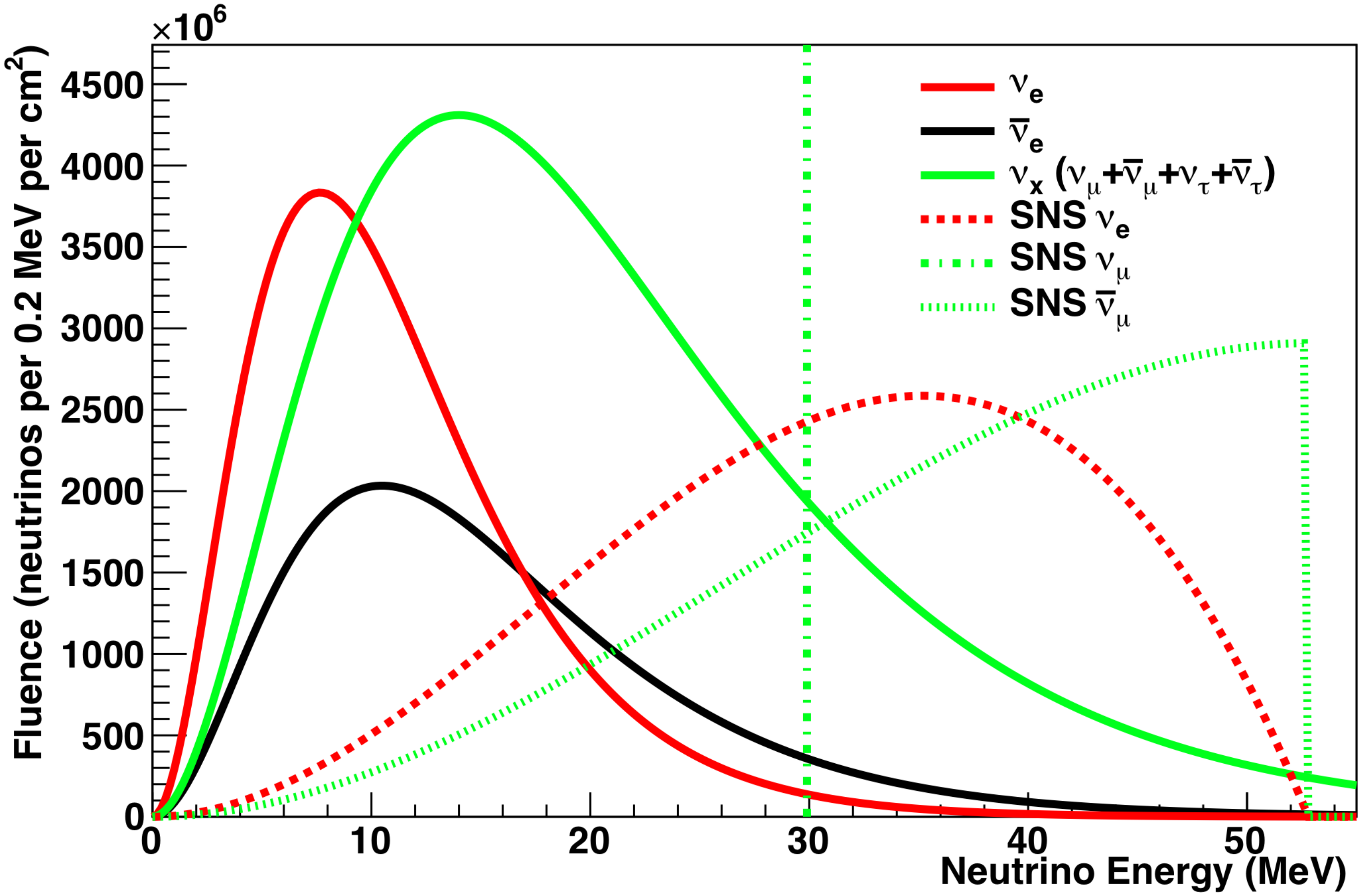
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ PROMPT

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

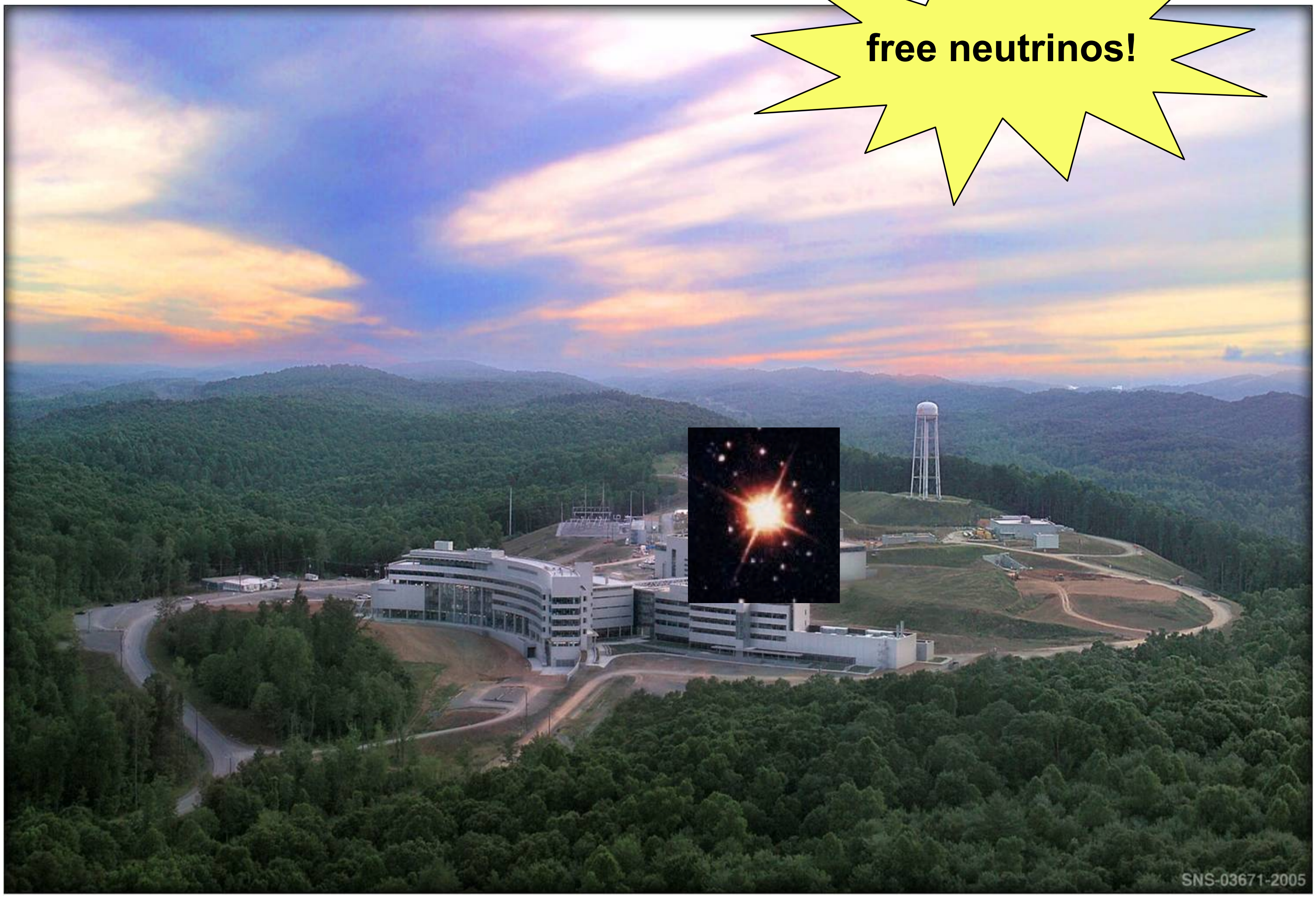
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

Supernova neutrino spectrum overlaps very nicely with stopped π neutrino spectrum



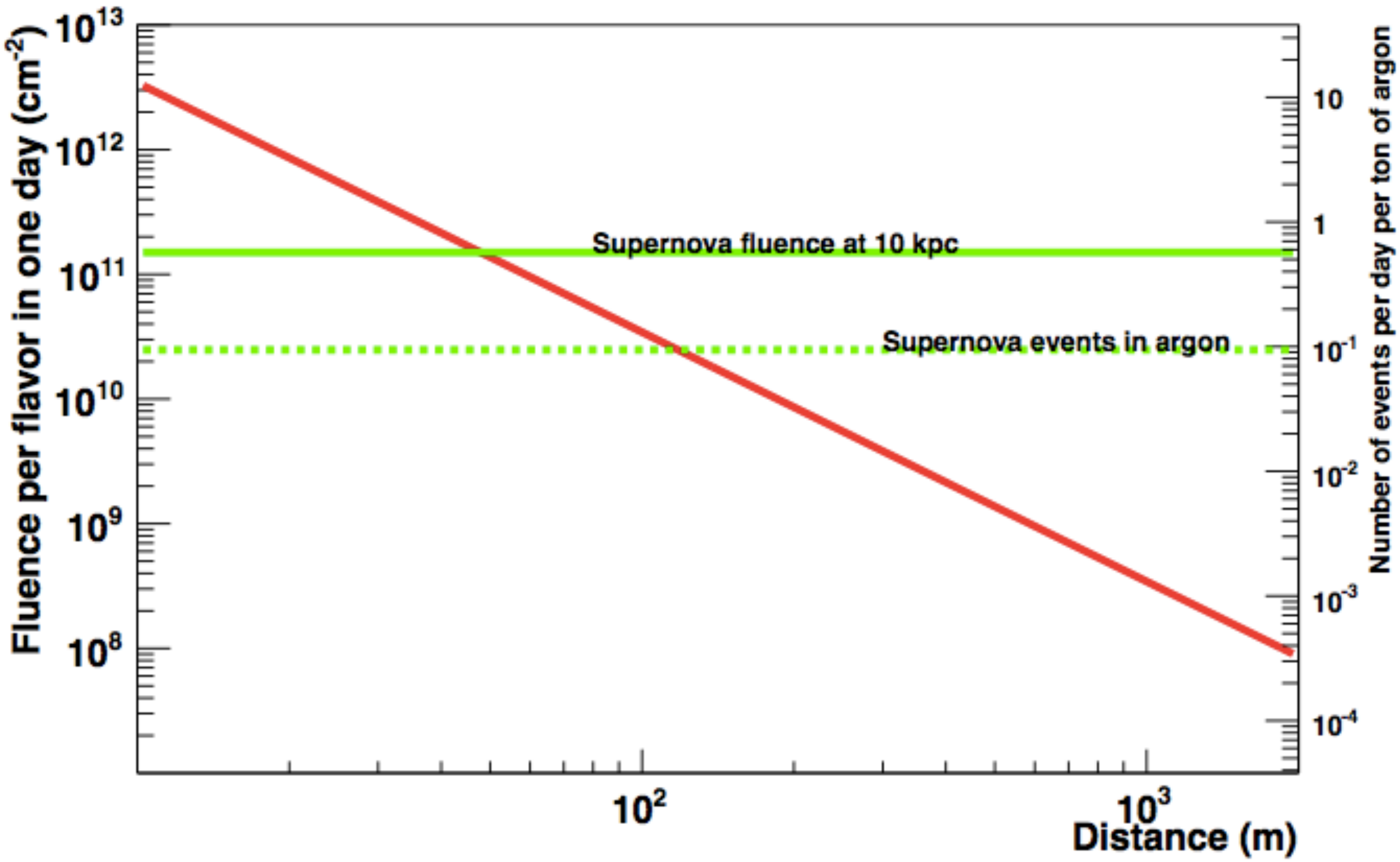
Study CC and NC interactions with various nuclei, in few to 10's of MeV range

The Spallation Neutron Source
Oak Ridge, TN

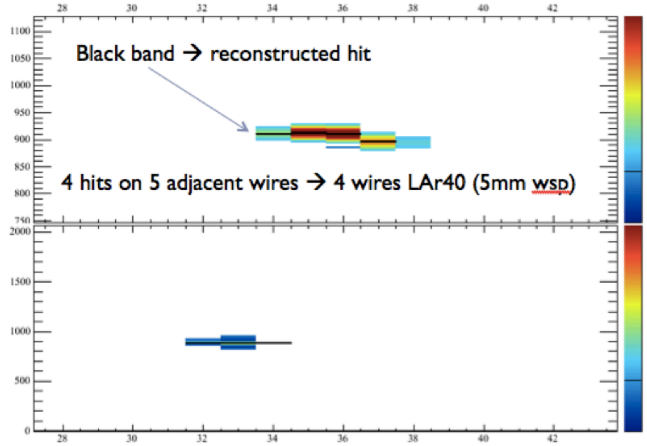


Fluence at ~50 m from the SNS amounts to ~ a supernova a day!

(and effectively more events due to harder spectrum)



Background for supernova ν's in LAr

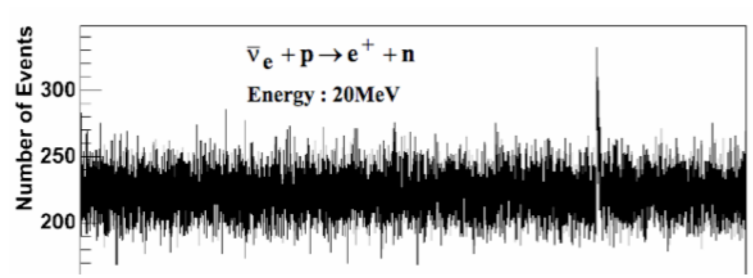


Signal is "crummy little stubs" and vulnerable to bg
(γ tagging could help)

- **muons & associated Michels:** should be identifiable
- **radioactivity: mostly < 5 MeV**
- **cosmogenics**

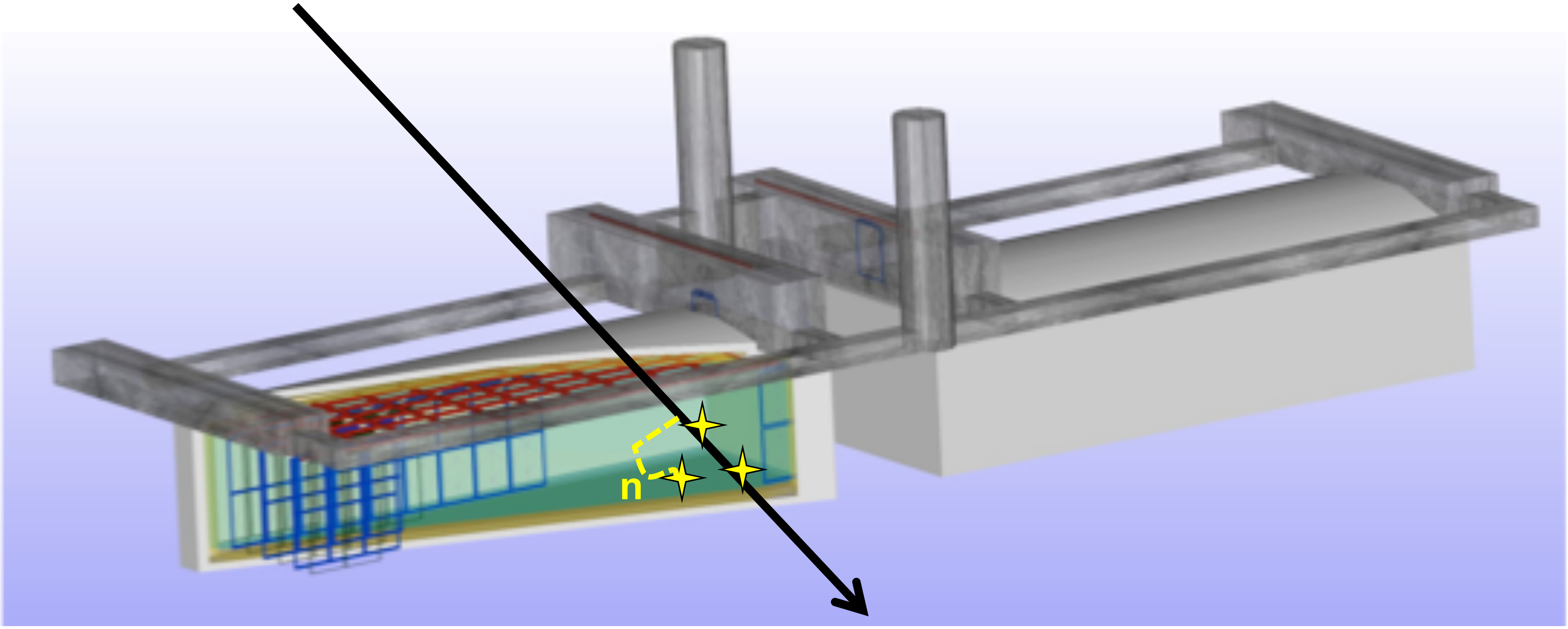
How shallow is OK?

NOνA, MiniBooNE, μBooNE get *something*, if background-ridden (and bg can be *known*)



NOνA

Cosmogenic backgrounds in LAr



- cosmic rays can rip apart nuclei, leaving radioactive products that can decay on ms-hour (day, year..) timescales
- neutrons, muon capture can also be problematic
- fairly well understood in water & scintillator, but few studies in argon

- in principle can be associated with parent muons (need photons...)
- in principle mitigation strategies exist (e.g. γ tagging) but efficiency currently unknown

Cosmogenic products

From Barker, Mei & Zhang, arXiv:1202.5000 **(are G4 cross-sections OK??)**

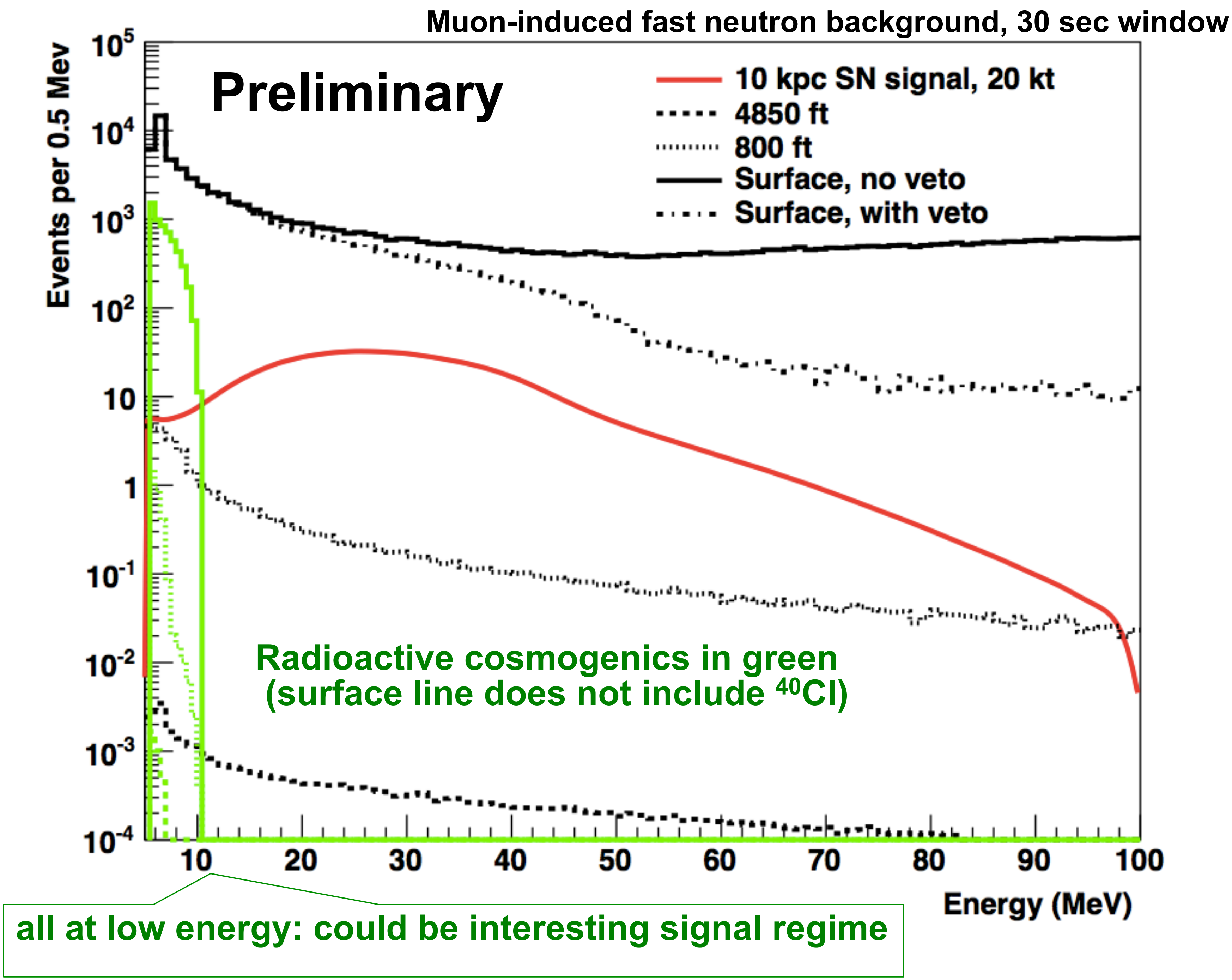
TABLE II: Additional significant cosmogenic production rates in the detector (20 kton) at the 800-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9020	4.23	2.5 m
^{32}P	Spallation	20900	1.71	14. 3 d
^{33}P	Spallation	30100	0.25	25.3 d
^{34}P	Spallation	12090	5.4	12.4 s
^{35}P	Spallation	7500	4.0	47. 2 s
^{36}P	Spallation	1190	10.4	5.6 s
^{37}P	Spallation	550	7.9	2.3 s
^{31}S	Spallation	5500	5.4	2.6 s
^{35}S	Spallation	215500	0.17	87.5s
^{37}S	(n,α)	31500	4.9	5.1 m
^{38}S	Spallation	11500	2.9	170 m
^{39}S	Spallation	850	6.6	11.5 s
^{33}Cl	Spallation	670	5.6	2.5 s
^{34}Cl	Spallation	8700	5.6	32 m
^{36}Cl	Spallation	1005000	0.7	3.1×10^5 y
^{38}Cl	Spallation	110000	4.9	37.24 m
^{35}Ar	(n,6n$'$)	7100	6.0	1.8 s
^{37}Ar	(n,4n$'$)	21000	0.8	35 d
^{39}Ar	(n,2n$'$)	91000	0.57	269 y
^{41}Ar	capture	45100	2.5	109 m
^{38}K	Spallation	650	5.9	7.6 m
^{40}K	(p,n)	6500	1.3	1.28×10^9 y
Total		1641920		

TABLE IV: Additional significant cosmogenic production rates in the detector (20 kton) at the 4850-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9.6	4.23	2.5 m
^{32}P	Spallation	22.2	1.71	14. 3 d
^{33}P	Spallation	31.9	0.25	25.3 d
^{34}P	Spallation	12.8	5.4	12.4 s
^{35}P	Spallation	8.0	4.0	47. 2 s
^{36}P	Spallation	1.3	10.4	5.6 s
^{37}P	Spallation	0.6	7.9	2.3 s
^{31}S	Spallation	5.8	5.4	2.6 s
^{35}S	Spallation	228.5	0.17	87.5s
^{37}S	(n,α)	33.4	4.9	5.1 m
^{38}S	Spallation	12.2	2.9	170 m
^{39}S	Spallation	0.9	6.6	11.5 s
^{33}Cl	Spallation	0.7	5.6	2.5 s
^{34}Cl	Spallation	9.2	5.6	32 m
^{36}Cl	Spallation	1065.7	0.7	3.1×10^5 y
^{38}Cl	Spallation	116.6	4.9	37.24 m
^{35}Ar	(n,6n$'$)	7.5	6.0	1.8 s
^{37}Ar	(n,4n$'$)	22.3	0.8	35 d
^{39}Ar	(n,2n$'$)	96.5	0.57	269 y
^{41}Ar	capture	47.8	2.5	109 m
^{38}K	Spallation	0.69	5.9	7.6 m
^{40}K	(p,n)	6.9	1.3	1.28×10^9 y
Total		1741		

- -assume β-decay spectral form for given Q value
- -normalize by rate per day from table
- -add all contributions
- -smear with LAr resolution from Amoruso paper


Muon-induced fast neutron background, 30 sec window
Preliminary
10 kpc SN signal, 20 kt
4850 ft
800 ft
Surface, no veto
Surface, with veto
Events per 0.5 Mev
Energy (MeV)
Radioactive cosmogenics in green
(surface line does not include ^{40}Cl)
all at low energy: could be interesting signal regime

Summary

Liquid argon has unique sensitivity to SN physics thanks to electron neutrino sensitivity

No measurements of low-energy ν-Ar cross-sections & interaction products exist

Need to understand detector response

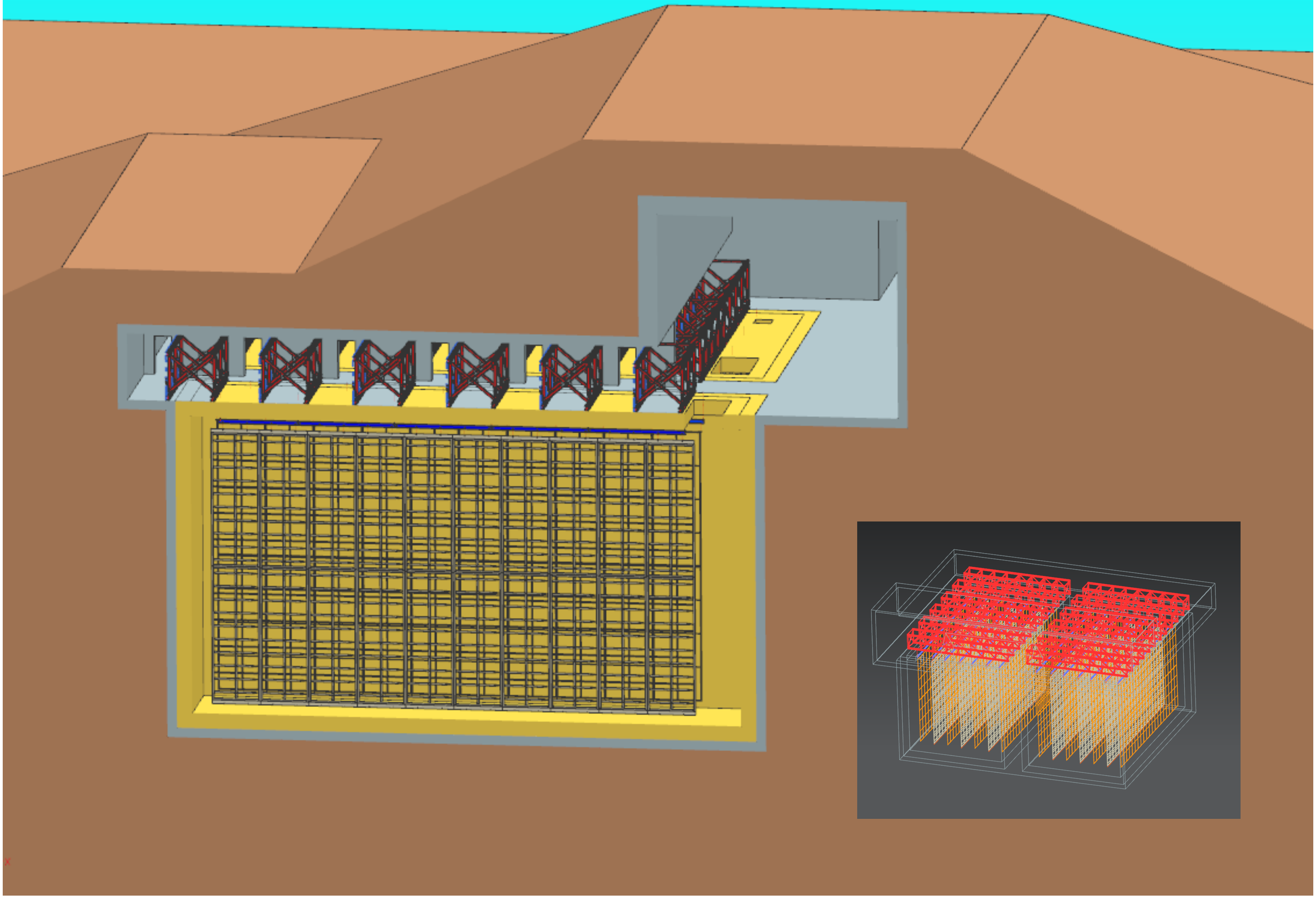
Need to understand backgrounds;
measurements could help..

... is surface running possible?

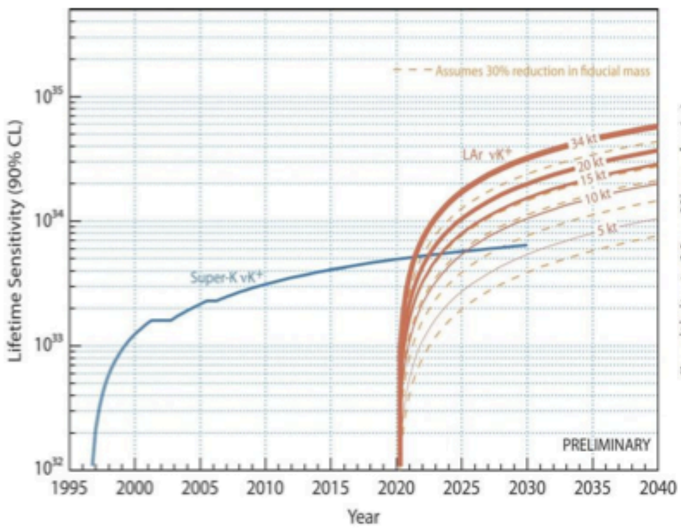
SNS = Supernova Neutrino Substitute (for free! just need the detector)

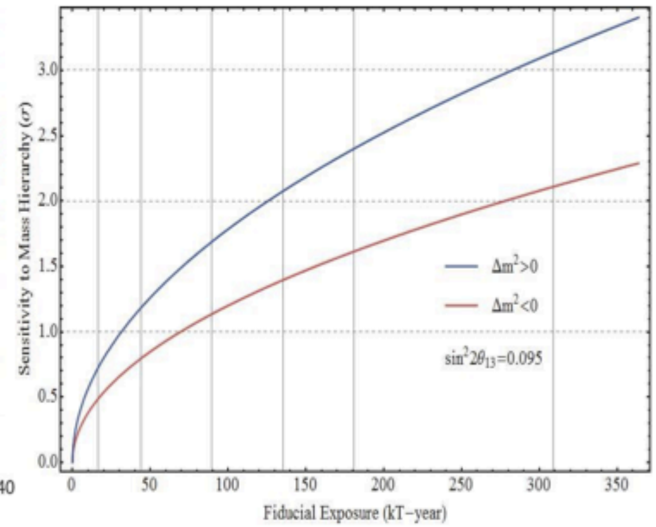
Backups/Extras

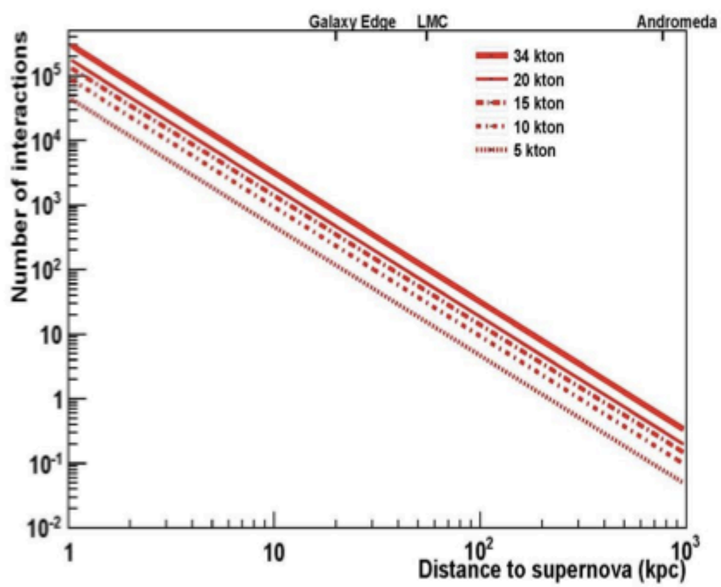
10 kton LAr on the surface at Homestake



Non-beam physics, possible underground

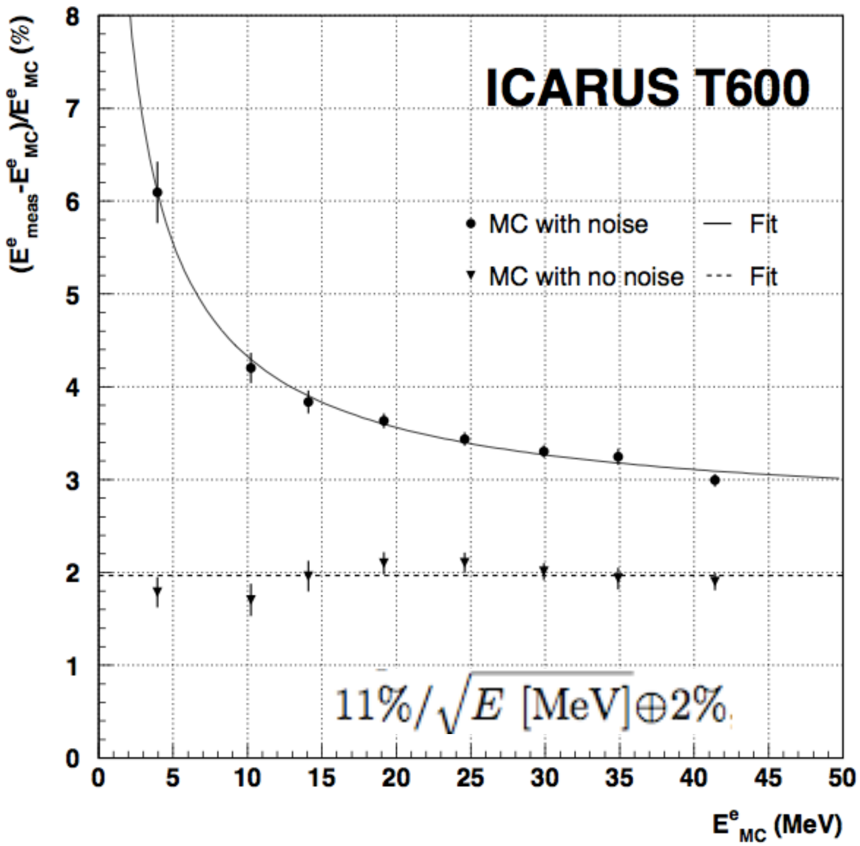


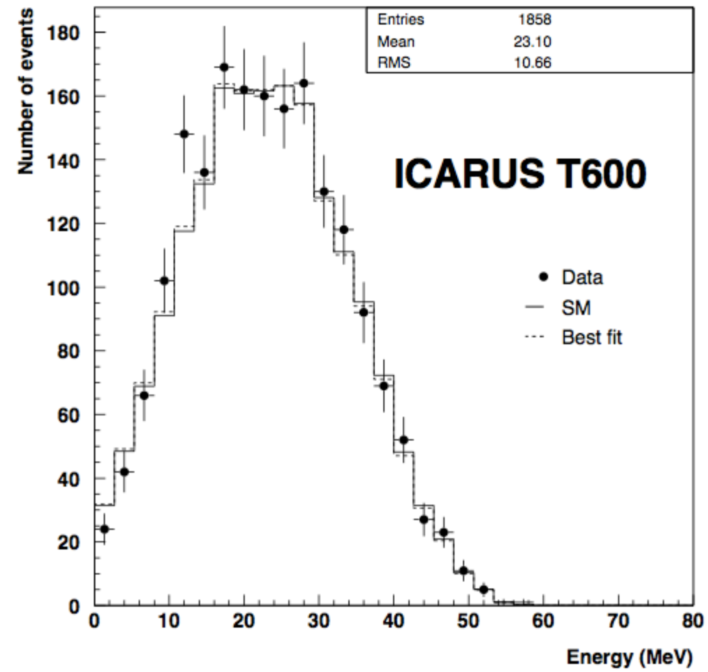




ICARUS resolution
(what's in SNOwGLoBES)

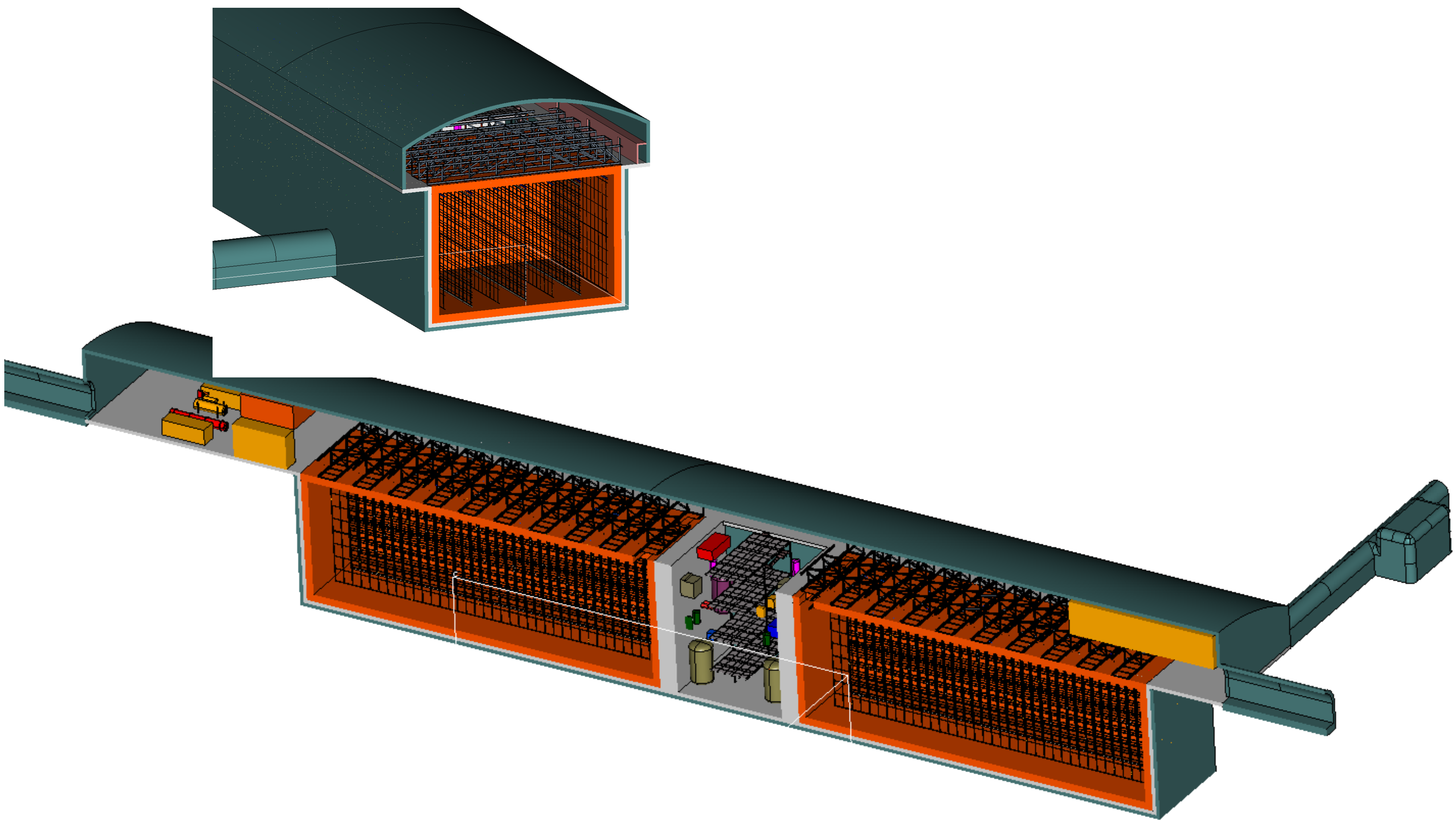
Amoruso et al., hep-ex/0311040





uses MC tuned to measured Michel electrons

Does not include "calorimetric" correction from drift time (~5%?)



Tool for evaluating neutrino event rates

To evaluate sensitivity to different features of flux/physics, we need to fold

$$\text{flux} \otimes \text{xscn} \otimes \text{detector response}$$

Software package to make use of the GLoBES front-end rate engine (*not* the oscillation sensitivity part)

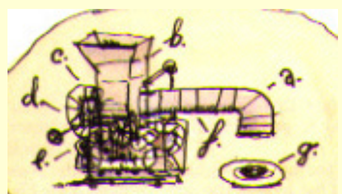
flux differential spectra w/physics

cross- sections for relevant channels

smearing matrix for given detector config: includes both interaction product distributions and detector response

post-smearing efficiency

SNOw GLoBES



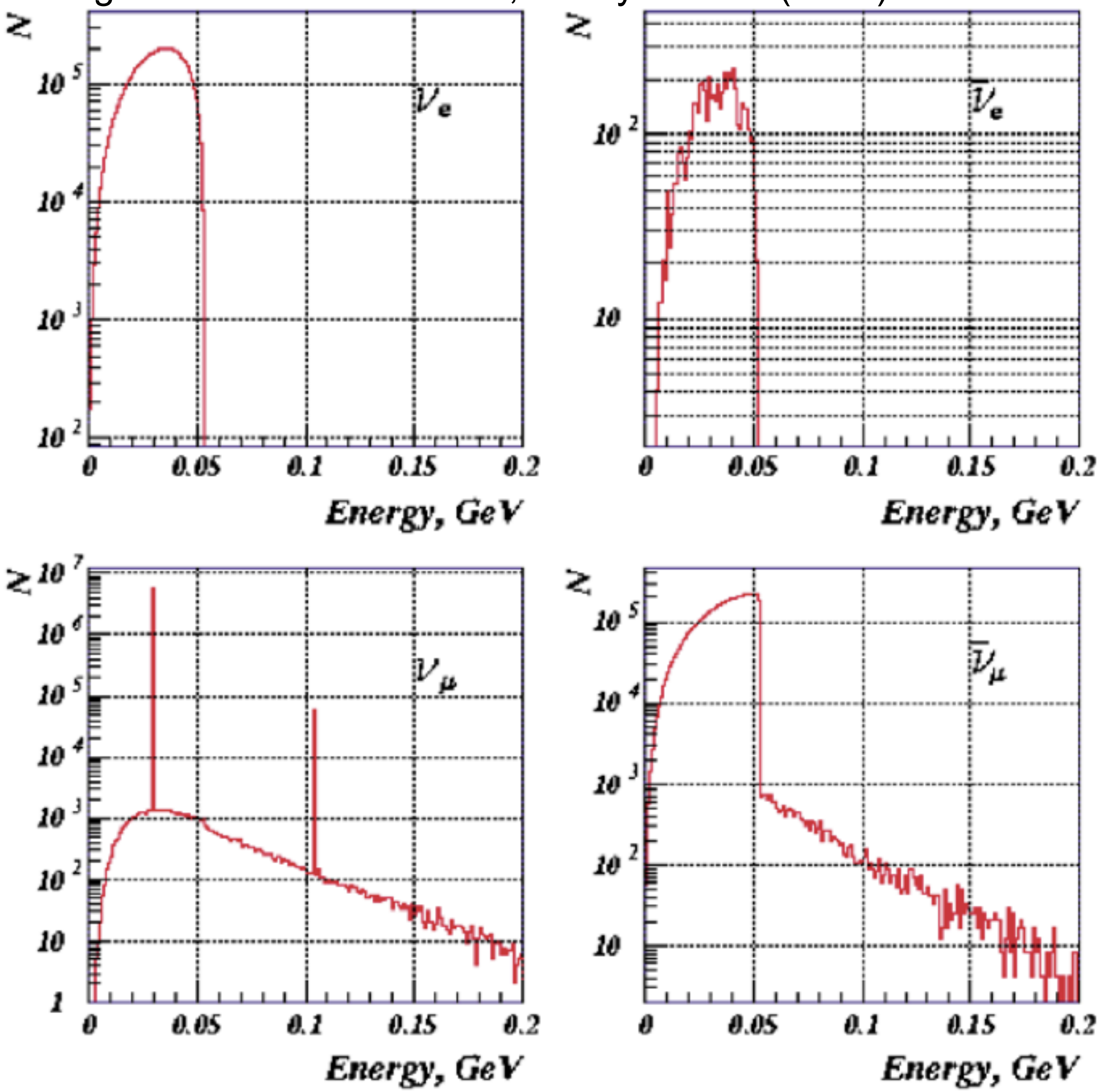
interaction rates, as a function of neutrino energy

'smeared' rates as a function of detected energy

what we're after

Flux calculation: clean spectrum

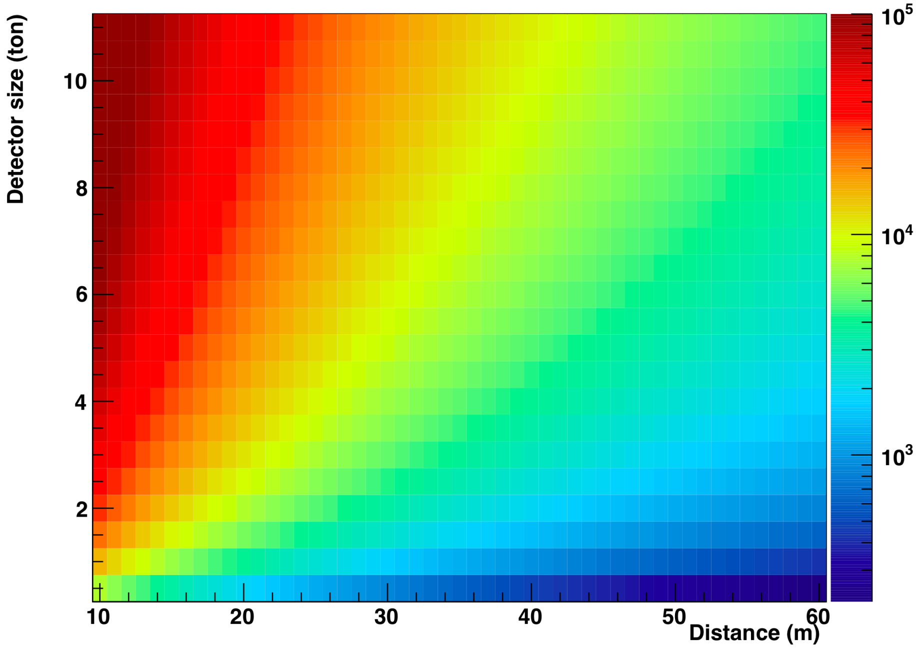
F. Avignone and Y. Efremenko, J. Phys. G: 29 (2003) 2615-2628



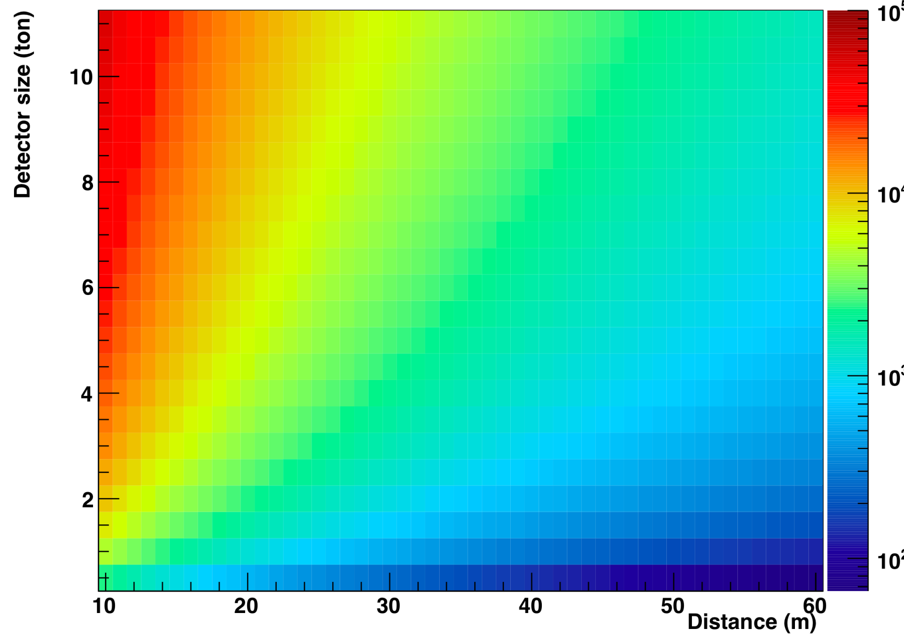
Total events per year at the SNS as a function of distance and mass

$$\propto 1/R^2, \propto M$$

lead



argon

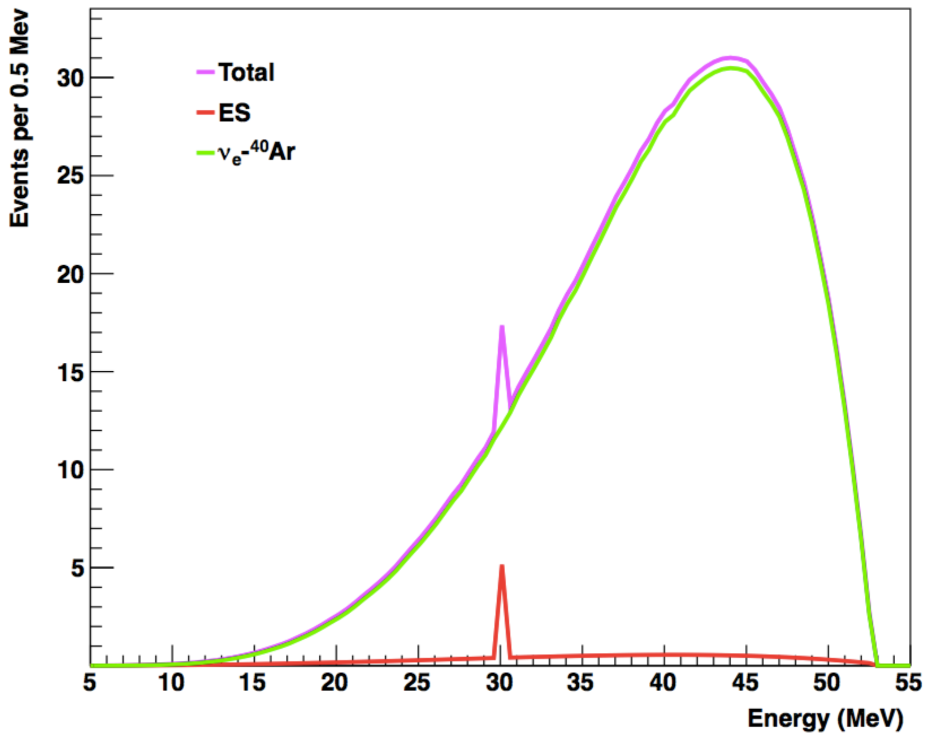


Scaling for another source: α power; duty factor is critical for background rejection

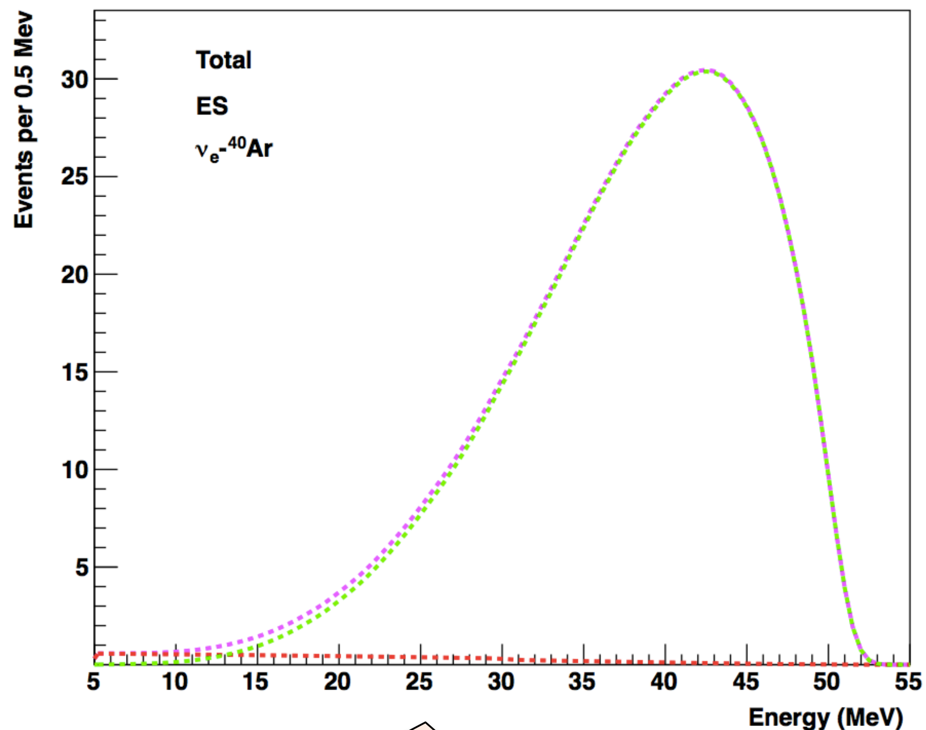
Event rates for argon at the SNS

per ton per year at 20 m

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy



Assumes 100% efficiency,resolution from Amoruso et. al. (ICARUS)